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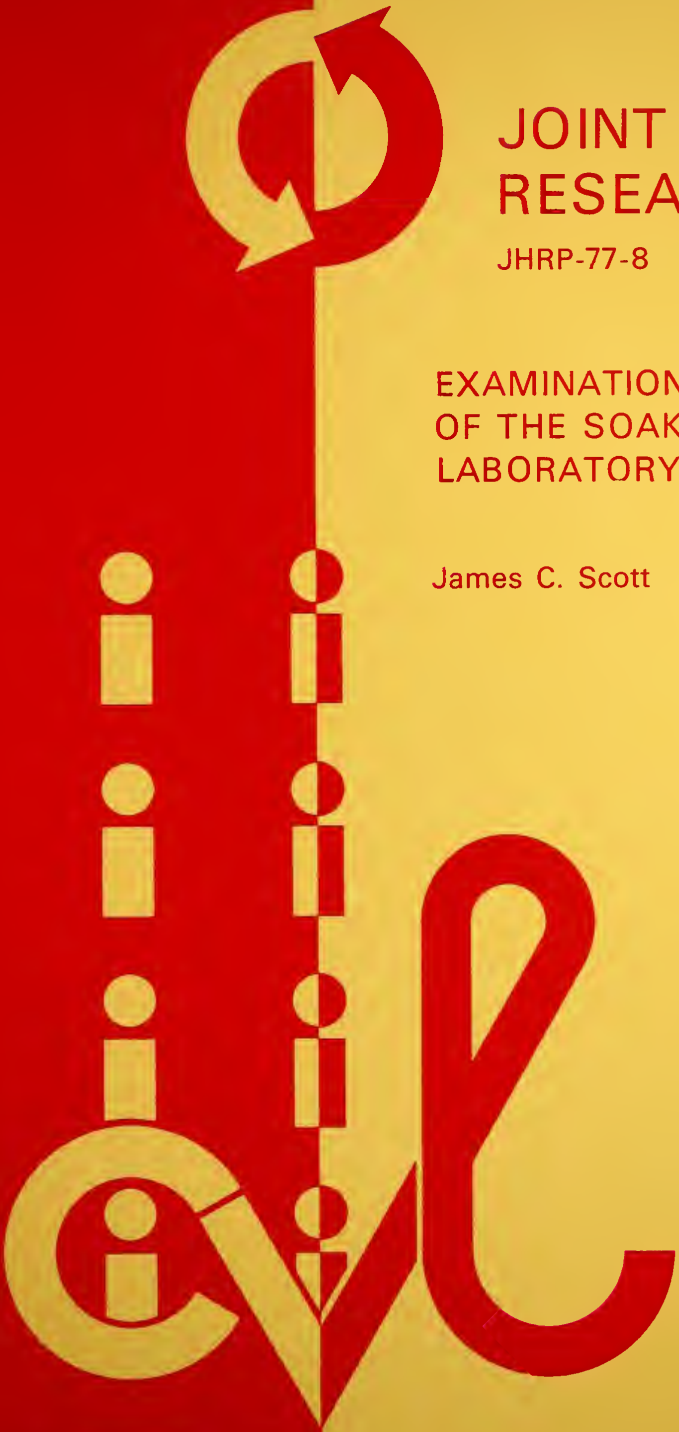

# JOINT HIGHWAY RESEARCH PROJECT

JHRP-77-8

## EXAMINATION OF THE VARIABILITY OF THE SOAKED STRENGTH OF A LABORATORY COMPACTED CLAY

James C. Scott

PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

Interim Report

# EXAMINATION OF THE VARIABILITY OF THE SOAKED STRENGTH OF A LABORATORY COMPACTED CLAY

May 16, 1977

Project: C-36-5M

File: 6-6-13

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

The attached Interim Report is submitted on the HPR Part II Study titled "Improving Embankment Design and Performance". This is Interim Report No. 3 on this Study and is titled "Examination of the Variability of the Soaked Strength of a Laboratory Compacted Clay". It has been authored by Mr. James C. Scott, Graduate Instructor in Research on our staff under the direction of Professor A. G. Altschaeffl.

The Report is of research devoted to evaluating the variability and the source of that variability in the soaked strength of a laboratory compacted silty clay. It is believed that the laboratory and field soaked strength functions will correlate well. This is a part of continuing research in this Study.

This Report is submitted in partial fulfillment of the objectives of this Study. Following acceptance by the JHRP Board it will be forwarded to ISHC and FHWA for review, comment and similar acceptance. As you know an extension of this Study is also included in a Proposal which was recently submitted.

Respectfully submitted,

Harold L Michael

Harold L. Michael
Associate Director

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Interim Report

# EXAMINATION OF THE VARIABILITY OF THE SOAKED STRENGTH OF A LABORATORY COMPACTED CLAY

by

James C. Scott
Graduate Instructor in Research

Joint Highway Research Project
Project No.: C-36-5M
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Prepared as Part of an Investigation

Conducted by

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in cooperation with the

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and the

U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Purdue University
West Lafayette, Indiana
May 16, 1977

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16. Abstract

A glacial silty clay was studied to determine what variables control the laboratory compacted soaked strength and its variability. The clay was compacted by the impact method at three different compactive efforts. In addition, a comparison with a laboratory as-compacted strength study on the same soil was made as a means of examining changes in strength and its variability.

It was found that the soaked strength for specimens compacted dry of optimum was a function of energy, the interaction of water content and energy, and the interaction of dry density and energy. For specimens compacted wet of optimum, the soaked strength was found to be controlled by molding water content only.

A prediction technique was developed using the laboratory soaked strength data that should ultimately be applicable for field data. If a designer selects a soaked strength desired for the compacted soil, and the variability he will accept, the technique will tell him the density, water content, and energy to specify for compaction of that soil using a specific type of compaction. Field data on a similar soil type are now being analyzed to demonstrate this technique for field compaction predictions.

17. Key Words
Compaction; compressive strength; dry density; laboratory; soil; soil variability; statistical analysis

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# HIGHLIGHT SUMMARY

This is the third interim report for this project. The objectives of this part of the research project include evaluating the variability and source of variability of the soaked strength of a laboratory compacted silty clay. Ultimately, a prediction of the in-service properties of the field compacted mass from laboratory data is desired.

A laboratory soaking procedure was developed to simulate the environmental change of increase in the degree of saturation from the compacted condition. Test data were generated by impact compaction for a glacial silty clay. For compaction dry of the optimum water content, the variables found to control the magnitude of the unconfined soaked strength were: the energy level, the interaction of dry density and energy, and the interaction of water content and energy. The magnitude of the unconfined soaked strength for specimens compacted wet of the optimum water content was controlled solely by the molding water content. All three energy levels used for this study showed that the soaked strength decreases much more rapidly on the dry side of optimum than on the wet side.

The variability in soaked strength was controlled by the magnitude of soaked strength and the interaction of water content and soaked strength.

A comparison is made with a companion laboratory study on as-compacted strength variability. The influence of these differences on compaction specifications is also discussed.

A prediction technique used in this study should ultimately be applicable for field data. If a designer selects a soaked strength desired for the compacted soil, and the variability he is willing to accept, the technique will tell him the density, water content, and energy to specify for compaction of that soil using a specific type of compaction. Field data on a similar soil type are now being analyzed to demonstrate this technique for field compaction, and to correlate the laboratory and field soaked strength functions.

# ACKNOWLEDGMENTS

The author is grateful to the Joint Highway Research Project, the Indiana State Highway Commission, and the Federal Highway Administration for their financial support of this study.

The author wishes to express special thanks to Professor A.G. Altschaeffl for his assistance and guidance throughout the course of this study.

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| $w$ | Water Content (%) |
| $\gamma_d$ | Dry Density (pcf) |
| $q_u^s$ | Unconfined Soaked Strength (psi) |
| $\bar{w}$ | Mean Moisture Content within Statistical Subset |
| $\bar{\gamma}_d$ | Mean Dry Density within Statistical Subset |
| $\bar{q}_u^s$ | Mean Unconfined Soaked Strength within Statistical Subset |
| $S(\gamma_d)$ | Standard Deviation of Dry Density within Statistical Subset |
| $S(q_u^s)$ | Standard Deviation of Unconfined Soaked Strength within Statistical Subset |
| $E$ | Energy Ratio = Ratio of the compactive energy of a test series to the lowest compactive energy used |
| $w_L$ | Liquid Limit (%) |
| $w_p$ | Plastic Limit (%) |
| $G_s$ | Specific Gravity of Solids |
| $R^2$ | Coefficient of Determination |
| $\alpha$ | Probability of a Type I Error |
| $b_o, b_1$ | Parameters of the Regression Equation |
| $\beta_o, \beta_1$ | Parameters of the Regression Model |
| $\varepsilon_i$ | Random Error |
| $S$ | Sum of the Square of Errors |
| $X$ | Independent Variable |
| $X_i$ | Independent Variable Corresponding to the ith observation |

## LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

| | |
|---|---|
| $Y$ | Response or Dependent Variable |
| $Y_i$ | Response or Dependent Variable Corresponding to the ith observation |
| $\bar{Y}$ | Mean Value of the Dependent Variable |
| $\hat{Y}$ | Predicted Value of Y |
| $n$ | Sets of Observations |
| $\sigma$ | Standard Deviation |
| CBR | California Bearing Ratio |
| ISHC | Indiana State Highway Commission |
| SPSS | Statistical Package for the Social Sciences |

# INTRODUCTION

Soil compaction is a mechanical densification process which produces a reduction of the air voids within the earthen material at a relatively unchanged water content. This densification is performed to improve the engineering behavior of the soil mass, and, thus, to improve performance in-service. The type and level of compaction should depend on the engineering properties required to insure acceptable performance of the completed structure. Because the usual civil engineering structure has a relatively long service life, concern must be shown for changes that may occur in the compacted mass during this life; these changes, then, should be incorporated into the decision about original compaction specifications.

Compacted soils are generally placed in a partially saturated condition. During the construction of a compacted fill there is usually control of the placement water content. After compaction, it is reasonable to assume that the compacted fill can at times approach a condition of saturation. There is always the possibility that the fill could become saturated by abnormal rainfall, ineffective drainage, impoundment of water, or seasonal variations in rainfall infiltration. Thus, the in-service behavior becomes of major

concern when a designer prepares compaction specifications. Unless the designer is certain that the compacted fill will never become saturated, he must design the fill on the basis that the water content may increase with time to a high degree of saturation.

If the water content changes after compaction, then the strength properties of the compacted fill will also change. The compacted soil may have a high strength in the as-compacted state, yet under light loading conditions the strength may be severely reduced upon saturation. Because of this, it becomes necessary that a designer know in-service relationships for his soil's behavior.

The purpose of this research is to study the in-service behavior of compacted soils. This report is a companion report to the research performed by Essigmann (1976) on the as-compacted behavior of compacted soils. A program of laboratory testing was used to simulate environmental changes by increasing the degree of saturation of laboratory compacted specimens, initially only partially saturated, to high degrees of saturation. The specimens were then tested for unconfined soaked strength. This soaked strength was used as a behavioral measure and the variability of this strength was examined.

This research is part of an attempt to develop predictability of post-compaction behavior. It attempts to develop laboratory relationships for soaked strength and the

variability of soaked strength as functions of the placement variables: molding water content, dry density, and energy. In addition, a comparison with the companion laboratory study on as-compacted strength as a means of examining changes in strength and its variability will be given. Finally, the influence of these changes on the compaction specifications will be discussed.

# LITERATURE REVIEW

## Unsoaked Strength of Compacted Soils

The CBR test, Hveem Stabilometer, and the triaxial compression test have all been used to establish an index of stability, load or pressure which a soil can support without excessive deformation. Seed and Monismith (1954) tested a silty clay ($w_L$ = 37%, $w_p$ = 23%) using the above tests and concluded that for partially saturated soils, the stability may increase or decrease with increasing density depending on the criterion used to define stability. If the ultimate strength or stress at 20% strain is used, the stability will in general increase with density. If the stress required to cause 10% strain is used as the criterion, the stability may increase or decrease with increasing density. While the stability of a compacted soil at a given water content may increase or decrease, they concluded that (within the range of water contents and densities investigated), for a given degree of saturation, the stability will increase with an increase in density; for a given density, the lower was the degree of saturation the higher was the stability. Thus, the degree of saturation may be more important in determining stability than the water content and the stability or strength of a compacted soil depends on the criterion used to define it.

Leonards (1955) tested two clays, Fort Union clay and Mississippi loess, to isolate factors that affect the shear strength of unsaturated compacted clays. The two clays were compacted by the static method. Leonards found that a unique relationship existed between the void ratio at failure and the compressive strength. Woodsum (1951) discovered that swelling of compacted clays, when in contact with water, increases at a given confining pressure as the amount of compaction energy imparted to the soil is increased.

In a study performed at the Waterways Experiment Station on a silty clay (ML-CL), Foster (1955) developed laboratory and field relationships between molding water content, dry density, and strength (CBR). His relationships showed that at a constant molding water content, the as-molded CBR increases with increase in dry density up to a point, after which further increases in dry density resulted in a decrease in strength. He reasoned that when the combination of water content and density were such that no significant pore pressures developed, strength would increase with density. However, when pore pressures developed, an increase in density would produce a decrease in strength. The water content-density combination above which the decrease occurred could be defined by the line of optimums (a curve drawn through the peaks of water content-dry density curves).

While investigating the feasibility of using plastic films as moisture barriers to protect highway sub-soils

from losses of stability due to increase in water content, Bell (1956) performed soaked and unsoaked CBR tests on a silty clay (A-6) and a plastic clay (A-7-5) in accordance with a procedure developed by the Corps of Engineers (Corps of Engineers, 1951). At a given dry density, the unsoaked CBR decreased with increasing molding water content. At a constant molding water content, the unsoaked CBR increased with increasing dry density. These results occurred for both soils.

Seed and Chan (1961) presented the results of an extensive investigation performed to help explain some of the factors affecting the strength of compacted clays in the as-compacted condition. Density-strength-water content relationships for a silty clay ($w_L$ = 37%, $w_p$ = 23%) were determined using the kneading compaction method. A series of samples at different water contents using three different compactive efforts were tested and the strength required to cause 5% and 20% strain for each sample was recorded. When the strength was determined using the 5% strain criterion, there was a marked decrease in strength as the density increased beyond a certain stage. These reductions in strength were due to densities and water contents corresponding to high degrees of saturation or to conditions which were wet of the optimum water content. They appear to be associated with the more dispersed soil structures and the higher pore water pressures of samples compacted wet of optimum. When

the strength was determined using the 20% strain criterion, the relationship between dry density and strength for a given molding water content showed no decrease in strength with increasing density. Seed and Chan also note that the differences in soil structure and strength resulting from kneading and impact methods of compaction are small.

Casagrade and Hirschfeld (1960, 1962) performed Q tests (unconsolidated undrained) on Canyon Dam Clay ($w_L$ = 34%, $w_p$ = 15%) to study the effect of the molding water content and dry density on the strength characteristics of compacted clays. The tests were performed at confining pressures of 4 kg/sq cm and 1 kg/sq cm. Under a confining pressure of 4 kg/sq cm, the strength decreased substantially with increasing molding water content, but was practically independent of the molding dry density. They reasoned the strength was independent of molding dry density because essentially all of the dissolved air was driven into solution under the 4 kg/sq cm confining pressure. Specimens compacted at a given water content were compressed until they reached almost full saturation. Thus, they all had the same dry density at the beginning of the application of the deviator stress. At the 1 kg/sq cm confining pressure, the strength increased with molding dry density at a given molding water content and increased with decreasing molding water content at a given initial dry density. $\overline{Q}$ tests (Q tests with pore pressure measured) were also performed to investigate the

induced pore pressure at failure for compacted specimens. For specimens compacted several per cent on the dry or several per cent on the wet side of optimum, the induced pore pressure was small at low confining pressures and about 50% of the deviator stress at failure for high confining pressures. Specimens compacted at the optimum water content had induced pore pressure at failure equal to 20% of their strength at low confining pressures, while for high confining pressures the pore pressure was about equal to the full compressive strength. Blight (1963) concluded that the as-compacted strength of soils is due largely to negative pressures which exist in the pore water after compaction. These pore water pressures do not become positive until considerable loads are reached, provided the pore air pressures are allowed to dissipate to zero as the loading is applied.

Unconfined compressive strength data of an A-6(7) soil was obtained by Peterson (1975). Regression analysis for both Standard Proctor and Harvard Miniature compacted samples was performed. The "best fit" regression equations indicated that the magnitude of the unconfined strength was a function of the dry density and the cube of water content ($w^3$). The prediction equation for the Standard Proctor yielded a coefficient of determination, $R^2$, of 0.86, while for the Harvard Miniature samples a value of 0.92 was obtained.

Peterson (1975) also reported on the results of a one-way analysis of variance (ANOVA) performed on published data. The ANOVA was used to determine if data sets were significantly different from each other when their mean values and variances were compared. The molding water content, dry density, and strength (CBR) from different compaction processes were treated in the ANOVA. The compaction processes included both laboratory and field. A non-significant gain in strength with a significant change in dry density and a non-significant difference in water content across the energy levels was indicated by the ANOVA results. From these results, two conclusions were proposed. First, the as-compacted strength is a function of water content and not dry density and secondly, interactions of the variables and insufficient data may have masked the relations and caused the apparent non-effect. Further work performed by Essigmann (1976) and this research indicate that the interactions among the placement variables do have a significant affect on the as-compacted and soaked strength of a silty clay compacted in the laboratory.

Essigmann (1976) examined statistically laboratory strength relationships for a glacial silty clay (A-4(5)). His study included both the magnitude of the as-compacted shear strength and the as-compacted variation in shear strength. Regression relationships and a nomograph for as-compacted strength and strength variability prediction

were developed. Essigmann found that the most important variables controlling the as-compacted shear strength were the dry density and the interaction between dry density and molding water content. His study presents the first mention of an interaction term influencing the as-compacted shear strength results. The influence of this interaction disallows the one-on-one relationship established by previous investigators and may have caused them to be misguided at times. For the as-compacted variation in shear strength, the most important factors were the shear strength and the variation in dry density.

For this study, laboratory relationships will be established for soaked strength on the same soil used by Essigmann (1976). This study, together with Essigmann (1976), should add to the design tools for forecasting how to limit or control the as-compacted and in-service behavior of compacted soils to desired magnitudes by proper initial compaction specifications.

## Soaked Strength of Compacted Soils

In 1950, the Corps of Engineers presented a symposium on the development of a flexible pavement design method for airfields using the CBR test (Trans., ASCE, 1950). To be conservative, the Corps specified that a design should be based on moisture conditions comparable to those obtained in soaked laboratory specimens which were considered to approach the field-saturated condition. Their investigation

showed that the strength (CBR) results could be explained by the method of preparing the test specimens. The variations in strength (CBR) were related to the molding water content, initial dry density, and the method of compaction. It was also found that unconfined compression tests and triaxial shear tests using the low-strain criterion resulted in trends similar to those found in the CBR test for comparable test specimens. The Corps concluded the following:

1. CBR for all soils compacted statically, and soaked, showed an increase with an increase in molding water content at a constant dry density.
2. CBR for impervious, high-swelling soils compacted dynamically, and soaked, showed an increase with an increase in molding water content for a constant dry density.
3. CBR for low plasticity soils with little or no swell, compacted dynamically, and soaked, showed an appreciable decrease with a slight increase in molding water content for a constant dry density.
4. Laboratory soaked specimens with low plasticity compacted at the optimum water content or drier by the dynamic method have greater CBR values than corresponding specimens compacted statically.
5. The four trends listed above for the CBR test were also found to occur in unconfined compression tests and quick triaxial tests when maximum strength and stresses at low strains were considered.

Changes in void ratio and degree of saturation with time will cause the strength properties of a compacted mass to change after compaction. To study these changes, Wilson (1952) used triaxial compression tests ($Q_c$, consolidated-quick) on clayey sand specimens compacted in the Harvard Miniature device. The degree of saturation was increased during consolidation by water circulation through the specimens. Unfortunately, the true degrees of saturation after soaking were not obtained (Wilson, 1977). Wilson discovered that the maximum soaked strength occurred for samples initially compacted at the optimum water content, and the soaked strength decreased rapidly on the dry side of optimum. Water contents of specimens compacted dry of optimum increased to well above the optimum water content while those compacted on the wet side showed only a slight increase in water content.

Freitag (1951) performed an investigation on the soaked strength of a silty clay. He compacted specimens to the same initial dry density but at different molding water contents by varying the compactive effort with the Harvard Miniature device. $Q_c$ (consolidated-quick) tests were performed on the specimens after a two day soaking period. After saturation, the specimens had approximately the same water content, degree of saturation, and dry density. The maximum soaked strength was developed for specimens compacted at the optimum water content, and lower strengths for

those compacted either wet or dry of optimum. The deviator stress corresponding to 2% strain for specimens compacted dry of optimum was more than twice that of those compacted at, or wet of, optimum.

The Hveem Stabilometer was used by Seed and Monismith (1954) to study the effects of the degree of saturation upon the stability of a clayey sand. They concluded that for a given degree of saturation, the R-value, a measure of stability, will increase as dry density increases. They found this equally true for all degrees of saturation, including 100% saturation.

A unique relation between the shear strength and the water content at failure for saturated clays was observed by Rutledge (1947). Leonards (1955) discussed the reason for the difference in strength behavior between partially saturated and saturated compacted clays. He reports that for a saturated clay, a change in void ratio must be accompanied by a corresponding change in water content while for partially saturated clays, changes in void ratio can occur without any change in water content.

While investigating the uplift caused by expansive clays when saturated, Holtz and Gibbs (1956) examined the loss of shear strength upon saturation. When clays expand with increased saturation, the shearing strength became less and the dry densities decreased. For example, a CH soil ($w_L$ = 75%, $w_p$ = 25%) had a dry density of 103 lb/cu ft, a degree

of saturation of 93%, and an unconfined compressive strength of 155 lb/sq in in its natural state. Upon wetting under no loading, the dry density became 85.7 lb/cu ft, the degree of saturation 99%, and the unconfined compressive strength was reduced to essentially zero. The strength loss upon wetting of a compacted Porterville clay, CH ($w_L$ = 57%, $w_p$ = 20%), resulted in the soil, initially at a degree of saturation of 70% at the optimum water content of 22% and an unconfined compressive strength of 28 lb/sq in, to increase to a degree of saturation of 94% while the strength was reduced to 4 lb/sq in. One can clearly see that the strength of compacted soils can be reduced considerably upon saturation, even though the soils may have fairly high strength at moderate moisture conditions.

Soaked CBR relationships for a lean clay (ML-CL) were developed by Turnbull and Foster (1956). The effect of increase in water content after compaction was studied by compacting specimens at a range of water contents and compactive efforts and subjecting the specimens to a soaking procedure before making the CBR tests. A surcharge weight equal to the weight that would be above the material in the field was used to confine the specimens during soaking and testing. It was discovered that the molding water content had as much or more influence on the CBR results than the water content reached in the soaking test. The soaking tests yielded a large loss in the CBR for materials compacted

dry of optimum, a smaller change for those compacted at optimum, and only a slight change for samples compacted on the wet side of optimum.

The soaked CBR test results obtained by Bell (1956) for a silty clay (A-6) showed that for a given molding water content, the CBR increased with dry density. His results for a plastic clay (A-7-5) showed the soaked CBR to increase to a maximum and then decrease with increasing density. Uppal (1969) and Uppal and Malhotra (1969) recognized that the strength of a compacted clay is adversely affected when the clay comes in contact with water. Inadequate strength may result with only a small increase in water content. To cope with this problem, Uppal (1969) recommended compacting subgrades on the wet side of optimum. This he believed would result in a higher soaked CBR than if the soil had been compacted at the optimum moisture content and subsequently saturated. To prevent subgrades and subbases from losing stability due to ingression of water, both Bell (1956) and Uppal (1969) suggested the use of moisture barriers.

The loss in shear strength of compacted loess upon saturation during the life of an embankment was examined by Kassiff (1957). Specimens of Negev loess (ML-CL) were compacted in the laboratory at different energy levels, saturated, and tested for shear strength by $Q_c$ (consolidated-quick) tests. The saturated specimens had lower strengths than the unsaturated because of higher pore pressures during

loading. Maximum soaked strengths were developed for specimens compacted near the optimum water content.

Yoder (1959) presents general trends of soaked CBR results for clayey soils. A peak value for the soaked CBR test results occurs similar to a compaction curve. The reason for the peak value is moisture absorption and swelling during soaking. The swelling tendencies for clays decrease as the molding water content increases up to about the optimum water content. Beyond the optimum water content, the swell becomes relatively constant for increasing water contents.

The Bureau of Reclamation, in addition to triaxial testing, developed their own testing procedure for compacted clays which may become wetted after placement (Gibbs et al., 1960). Briefly their procedure was to:

1. Compact a specimen to the same moisture and density conditions as other triaxial test specimens.
2. Determine the as-compacted weight and volume.
3. Wrap the specimen in two layers of cheesecloth and immerse in a water bath for two to seven days.
4. Determine the wetted weight and volume.
5. Test the specimen for strength while still sealed.
6. Determine the final water content.

Although this procedure did not result in a fully saturated specimen, the Bureau felt it stimulated changes in strength caused by wetting. The specimens which exhibited the

greatest loss of strength on wetting absorbed considerably moisture and obtained high degrees of saturation. Gibbs et al. (1960) conclude that since the sequence of loading and wetting affect the strength of compacted clays, it is important to duplicate field conditions closely.

Curves showing soaked strength (cone index) as a function of molding water content for Vicksburg Buckshot clay ($w_L$ = 63%, $w_p$ = 25%) were given by Lambe (1960). Dynamically compacted specimens were soaked under a low confining pressure of 200 psf. Specimens compacted on the wet side of optimum showed a slightly higher undrained soaked strength than those compacted dry of optimum. The greater water deficiency (water needed to fully develop the double layer) in the specimens compacted dry of optimum caused them to swell more than those compacted wet of optimum. Swelling during soaking was due primarily to an increase in the size of the micelle (system containing the electrically charged clay particle and the exchangeable cations that are attracted by the charged clay surface for maintaining an electrically neutral system). If swelling had been prevented, the specimens compacted dry of optimum would have had a higher undrained strength after saturation.

Seed et al. (1960) and Seed and Chan (1961) give results of a comprehensive study on the undrained strength of compacted soils after soaking. According to their study, the undrained soaked strength of a compacted clay depends on the following factors:

1. final water content.
2. structure after soaking.
3. change in structure as the specimen is loaded.
4. basis for determining failure.

For soaked strengths determined at high strain, 20%, the molding water content had no influence on the strength. However, for strengths determined at low strain, 5%, the lower the molding water content the higher the strength after soaking for a given initial dry density. It should be noted that the above results were from specimens soaked at constant volume.

Seed et al. (1960) investigated the effect of surcharge pressures on the relationship between initial composition and strength after soaking for an expansive sandy clay (CL). The molding water content had practically no effect on the strength after soaking under a high surcharge pressure (35 lb/sq in). However, under a low surcharge pressure (1 lb/sq in), the soaked strength increased slightly with molding water content at a given initial dry density.

Terzaghi and Peck (1967), Altschaeffl and Lovell (1968), and Sowers and Sowers (1970) stress that if a compacted mass approaches high degrees of saturation during its lifetime, the strength and strength characteristics may become significantly different than those at the time of placement. They express the feeling that a great deal of engineering judgment and experience is necessary to predict the ultimate

behavior of a compacted mass and that it is necessary to know the in-service properties of compacted soils.

The influence of initial compaction conditions on the as-compacted and in-service behavior of compacted soils must be recognized. Compaction specifications and design procedures should be coordinated with the physical properties of the compacted mass, both as-compacted and in-service. Past work has not solved the problems associated with compacted specifications for the in-service behavior of compacted soils. This study attempts to examine the effects of the initial compaction conditions on the in-service conditions and thus improve the capability for forecasting in-service behavior.

## Water Content Change of Compacted Soils Upon Soaking

Consolidated-quick triaxial tests performed by Wilson (1952) on a clayey sand resulted in the degree of saturation to increase during consolidation by water circulation through the specimens. Specimens compacted on the dry side of optimum had water contents at the end of soaking higher than the optimum water content. On the other hand, specimens compacted wet of optimum had only a slight increase in water content after soaking.

Many compacted clays under zero confining pressure will imbibe water until they reach a water content approximating the liquid limit even when compacted at molding water

contents less than the plastic limit (Ladd, 1960). Lambe (1958) explains the reason for this is clays compacted at low water contents have a high "water deficiency" and low degrees of saturation. The lower the molding water content, the greater is the water pickup required to satisfy the double-layer deficiency. Lambe (1960) reports that soaked samples imbibed much less water when soaked in salt water than in distilled water. Because of this, specimens soaked in salt water retained much more strength than those soaked in distilled water.

Seed et al. (1960) studied the influence of molding water content and soil structure on the swelling characteristics of a sandy clay (CL). They concluded that specimens compacted dry of optimum exhibited greater swelling tendencies and swelled to higher water contents than specimens of the same dry density compacted wet of optimum. They reasoned that water content increase upon soaking is due to 1) water content increase due to saturation and 2) water content increase due to swelling. The large change in water content for specimens compacted dry of optimum and hence increased swelling tendencies was believed to be the result of their flocculated structure. Alpan (1957), Holtz (1969), and Mitchell (1976) also believe soil structure to be an important factor influencing volume change of compacted clays.

Seed, Mitchell, and Chan (1962), Kayyal (1965), and Bhasin (1975) report that clays compacted on the dry side

of optimum exhibited greater volume increases due to soaking than those compacted on the wet side. For specimens compacted at a given molding water content on the dry side of optimum, higher compactive efforts resulted in greater increases in volume when soaked. It should be noted that the specimens were soaked under nominal surcharge pressures. Bhasin (1975) explains that specimens compacted on the dry side of optimum contain a considerable amount of large pores. When soaked, these specimens imbibe large amounts of water and swell considerably causing them to have low soaked strengths. Pore size distributions of specimens compacted wet of optimum are not greatly affected by soaking and therefore have strengths which are not significantly reduced after soaking.

When compacted clays are exposed to water, the swelling that occurs has been found to depend upon the initial water content, initial dry density, loading conditions, and the method of compaction (Chen, 1975). Low water contents and high dry densities cause compacted clays to swell the most. Swelling decreases with increasing confining pressure. Kneading and static compaction produce essentially the same swell for clays compacted dry of optimum, but static compaction results in greater swell for wet side compacted specimens (Seed, Mitchell, and Chan (1960)).

The role of mineralogy associated with swelling of clays has been investigated by Hardy (1965), Sultan (1969),

Uppal (1969), Holtz (1969), Chen (1975), and Mitchell (1976). They conclude that swelling is caused when water and other molecules enter between the unit layers of the caly mineral montmorillonite and expand the mineral's lattice. Pichler (1953) suggests that the amount of swell is proportional to the montmorillonite present in the soil.

Clays compacted dry of the optimum water content do not retain high strength when soaked prior to testing. Soaking results in an increase of the degree of saturation and water content. The increase in water content is more pronounced for clays compacted on the dry side of optimum than on the wet side. Unless a sufficient confining or surcharge pressure is applied during soaking to oppose swelling, the strength and dry density may decrease when compacted specimens are soaked.

# EXPERIMENTAL PROCEDURES

## Introduction

A program of laboratory testing which simulates environmental changes on compacted soil was made. The program consisted of soaking compacted specimens under low surcharge pressures, and then testing the specimens in unconfined compression. Relationships between molding water content, dry density, and soaked strength were then statistically developed to aid in the prediction of post-compaction behavior. Relationships involving the variability of soaked strength were also developed from the laboratory test data to help examine the variability of post-compaction behavior.

## Laboratory Testing Program

The laboratory testing program used for this research project involved two phases. Phase I of the research project is described in detail by Peterson (1975). The initial work in Phase II involved a study of laboratory compacted soil behavior in the as-compacted state and is described by Essigmann (1976). The major thrust of this research is directed toward the behavior of compacted soil in a soaked condition.

The soil used for testing was obtained from a borrow area for an embankment being constructed by the Indiana

State Highway Commission (ISHC), under project number STF-95(12), located near Carbondale, Indiana, during the summer of 1975. Bag samples were obtained from the borrow area and taken to the Soil Mechanics Laboratory at Purdue University. The soil was air dried, pulverized by hand, sieved to remove any material larger than 1/4 in. diameter, and stored in several large metal barrels. The soil tested was the same as that used by Essigmann (1976). Classification tests performed on the soil are summarized in Table 1. Figure 1 shows the grain size distribution curve for the soil tested. These results were obtained by Essigmann (1976).

Table 1. Classification Test Results

| | |
|---|---|
| Liquid Limit (%) | 20 |
| Plastic Limit (%) | 14 |
| Plasticity Index (%) | 6 |
| Specific Gravity of Solids | 2.73 |
| Unified Soil Classification | CL-ML |
| AASHO Soil Classification | A-4(5) |
| Description | Gray Clayey Silt |

To prepare specimens for testing, the impact method of compaction was used. Three different energy levels that will be referred to as the 15 Blow Proctor, the Standard Proctor, and the 25 Blow Proctor were used. These levels of energy are given in Table 2. The energy ratio shown in Table 2 is the compactive energy delivered to the soil during compaction

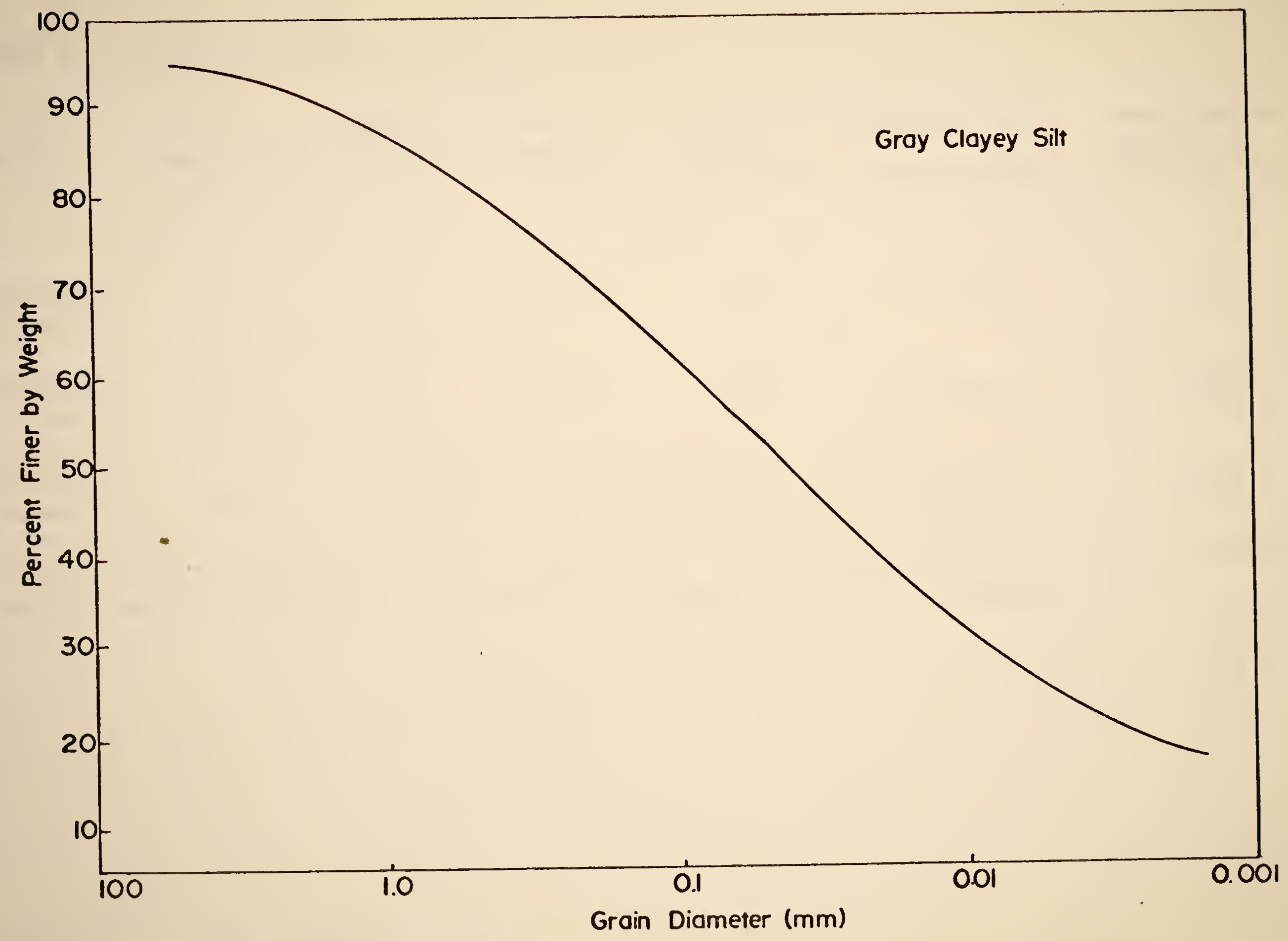

FIGURE I GRAIN SIZE DISTRIBUTION.

Table 2. Laboratory Compaction Tests Used

| Test Series * | Height of Hammer Drop (in) | Number of Layers | Weight of Hammer (lb) | Number of Blows Per Layer | Energy Used (ft-lb/cu ft) | Energy Ratio Used For Analyses, E |
|---|---|---|---|---|---|---|
| 15 Blow Proctor | 12 | 3 | 5.5 | 15 | 7,400 | 1.00 |
| Standard Proctor | 12 | 3 | 5.5 | 25 | 12,400 | 1.67 |
| 25 Blow Proctor | 18 | 3 | 10.0 | 25 | 33,750 | 4.56 |

* Mold size for all test series was 4.0 in. dia. x 4.6 in. height.

by each respective test series divided by the compactive energy used for the 15 Blow Proctor (7,400 ft - lb/cu ft). This energy ratio was used as a variable in the subsequent statistical analyses.

Six pounds of the presieved soil was used for each test. Water was added to the soil sample 24 hours before the time of compaction. To achieve the desired water content, a predetermined amount of distilled water was added and distributed evenly by means of a hand atomizer and mixed into the soil thoroughly by hand. After mixing, the soil, in a shallow steel pan, was sealed in a large polyethylene plastic bag and stored in a 55 gallon covered plastic barrel for a 24 hour curing period. Several inches of water were kept in the barrel to develop a humid atmosphere. Allowing the soil to cure for 24 hours enabled the soil samples to have a more uniform and homogeneous water content (Lambe, 1951).

Before compaction, the Proctor mold and sampling tubes were lubricated with a silicone oil. Samples were obtained after compaction by simultaneously pressing three sharpened thin-walled stainless steel tubes (3.5 in. long x 1.485 in. outside diameter with a 0.025 in. wall thickness) into the compacted soil by means of an hydraulic jack. Figure 2 shows the sampling process. After pressing the tubes into the compaction mold, the tubes were dug out of the mold. Samples were extruded from the tubes, ends were trimmed, diameter and height measurements made, and the samples weighed. The

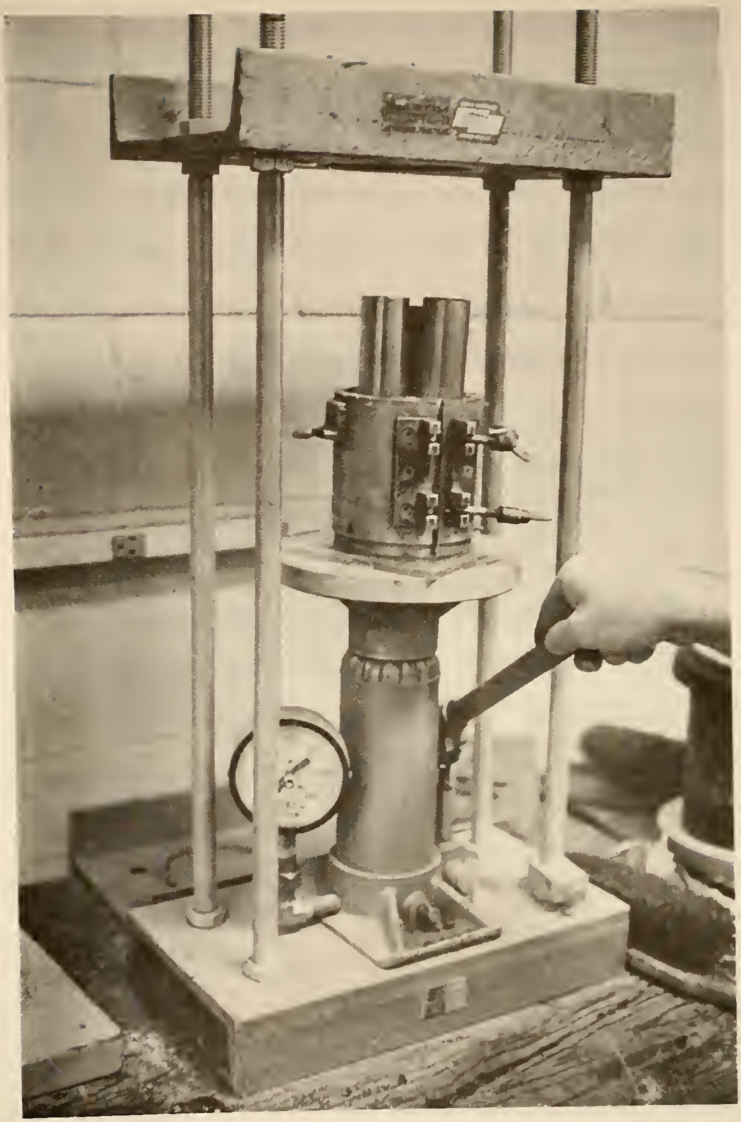

FIGURE 2 METHOD OF OBTAINING STRENGTH SAMPLES FROM PROCTOR MOLD.

samples were then put in small plastic bags, sealed, and stored in a humidifier at a constant room temperature of 22°C ($\pm$2°C) for five days. Highter (1969) showed evidence that measured strength appeared to decrease with time to some minimum value when Harvard Miniature compacted samples of a sandy clay were tested. Essigmann (1976) using Harvard Miniature samples of a clayey silt presented evidence that the compressive strength exhibits a minimum value at approximately five days after compaction. Because of these two studies, a five-day curing period was used.

## Soaking Apparatus and Procedure

In order to get the compacted specimens into a soaked (high degree of saturation) condition, a soaking apparatus and procedure were developed. The system was assembled and used in the Soil Mechanics Laboratory at Purdue University. Back pressure was used to increase the degree of saturation of the compacted specimens (Lowe and Johnson (1960), Corps of Engineers (1970)). To keep temperature variations to a minimum, all storing, soaking, and testing of the specimens took place in a controlled temperature room at 22°C ($\pm$2°C).

The equipment used to soak the specimens included triaxial cells, 3/8 in. diameter burettes, a 175 in.$^3$ water reservoir for back pressure, a small reservoir for top drainage, and a pressure regulator. One-quarter inch plastic tubing and quick-connectors were used to connect the cell pressure valves of the triaxial cells to the burettes. The

same type tubing was also used to connect the back pressure, controlled by the reservoir, to the bottom valves of the triaxial cells. Because of leakage around the pistons of the triaxial cells, the pistons were removed and replaced with rubber stoppers. The burettes were used to control and keep the cell pressure greater than the back pressure. By keeping the water levels in the burettes nine inches above the water level in the reservoir, the cell pressure was approximately 0.3 psi greater than the back pressure. The pressure regulator enabled a pressure of 50 psi to be applied at the water levels in the reservoir and burettes. Thus, a cell pressure of 50.3 psi and a back pressure of 50 psi were used to soak the compacted specimens. A schematic of the soaking system is shown in Figure 3. Figure 4 shows the entire setup.

Soaking of the specimens began after the five day curing period. Two of the three specimens from each compaction mold were soaked while the third specimen was used for an initial water content determination.

First, the base of the triaxial cell was saturated with deaired water. A sample to be soaked was removed from the humidifier and reweighed. A change in weight from the original weight was common but small. After weighing, a sample was placed immediately on the base of the triaxial cell and enclosed in two rubber membranes (combined thickness averaging 0.004 inches) as rapidly as possible to reduce the chance for any change in water content. The use of two membranes

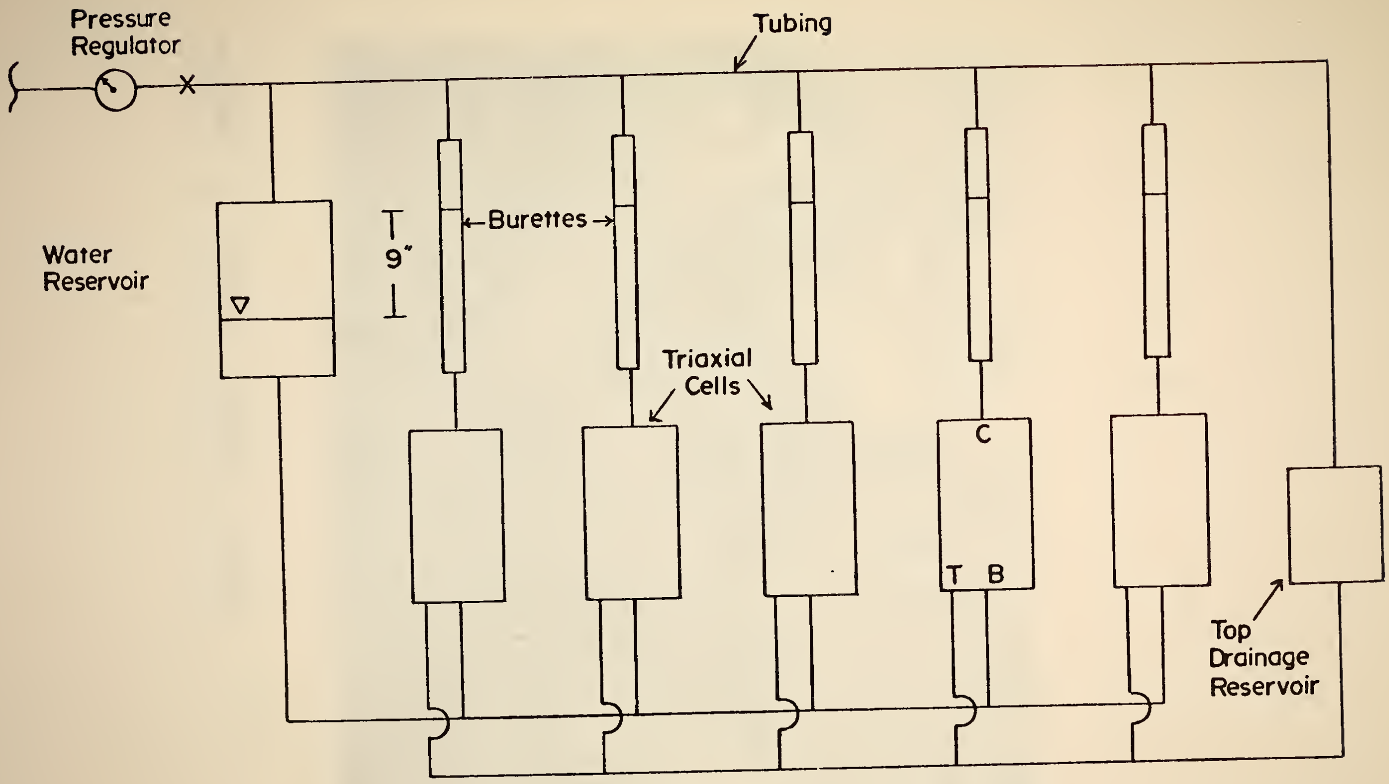

FIGURE 3 SCHEMATIC OF THE SOAKING SYSTEM.

[illegible]

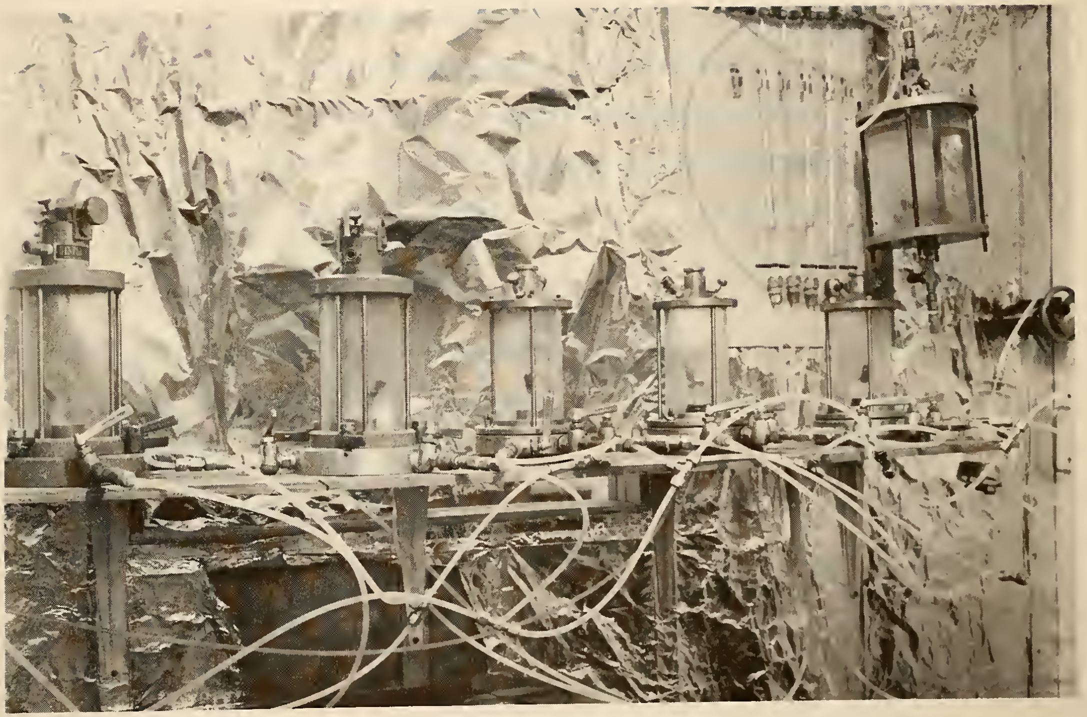

FIGURE 4 ENTIRE SOAKING SETUP.

afforded protection against leakage through undetected pinholes and minimized the possibility of air leakage from the chamber fluid into the specimen during the soaking period. A thin coating of silicone oil was applied between the two membranes to further help reduce leakage. A membrane stretcher was used to place the membranes over the specimen. Filter paper was placed between the sample and the top and bottom porous discs. The porous discs were saturated prior to use. O-rings were used to seal the membranes against the cap and base. After connecting the top drainage line to the cap, the triaxial cell was assembled and filled with chamber fluid. Deaired water was used as the chamber fluid. A few drops of deaired water were allowed to escape through a vent valve to insure complete filling of the chamber with fluid. The cell was then connected to the burette, back pressure reservoir, and top drainage reservoir. Once all cells were connected soaking was begun. Occasionally before testing, water remaining in the burrettes and tubing was drained and fresh deaired water put into the system.

To begin soaking, all valves were opened after making sure the water levels in the burettes (cell pressure) were higher than the water reservoir (back pressure). The cell pressure was raised evenly by the pressure regulator until a value of 50 psi was reached. At that time the burettes were adjusted so that they were nine inches above the water level in the reservoir. The nine-inch head difference

between cell and back pressure was checked frequently during the soaking period. A paper scale was attached to the back of each burette to monitor any swelling that might occur during the soaking period. Unfortunately due to leakage and small amounts of air in the system, swelling could not be measured accurately and consistently. However, monitoring was continued because it gave an indication if any leakage from the cell was occurring. Since the surcharge pressure was small, the specimens were soaked under essentially free swell conditions.

The compacted specimens were soaked for 48 hours (± 2 hrs.) Since all except 7 of the specimens soaked for 48 hours reached a degree of saturation greater than 95%, it was felt that 48 hours was an adequate time period for soaking. Wilson (1952) reports of an investigation on changes in strength properties of a silty clay after compaction performed by D.R. Freitag in which a two day soaking period was used.

After soaking, the soaked specimens were tested for unconfined compressive strength. Water was first drained from the triaxial cell and the headplate and transparent plastic cylinder were removed from the baseplate. The baseplate with soaked specimen was then placed in an unconfined compression apparatus developed at Purdue University. Essigmann (1976) provides a description of the apparatus and the X-Y plotter. The entire apparatus enabled the stress-strain

curves of the specimens to be plotted while strength testing was in progress. The plotter helped considerably to minimize the amount of data reduction.

The displacement rate for all specimens was 0.05 inches per minute. The time of loading to failure per sample for the unconfined compressive strength testing was about 12 minutes. Wilson (1952) loaded soaked compacted samples of clayey sand to failure within 5 to 10 minutes. Seed et al. (1960) used a time period of about 15 minutes to load soaked samples of compacted silty clay to failure.

The compressive strength of each specimen was defined as the maximum deviator stress or the stress at 20% strain, whichever occurred first. Typical stress-strain curves for the soaked samples are shown in Figure 5.

Once the sample had failed, a determination of the degree of saturation was made. The difficulty in making this determination was in measuring the bulk volume of the sample. First the sample was weighed in air. Next the sample was hand-dipped in a pot of straight melted Boronwax so that it had a thin coating of the wax completely enclosing the sample. Then the coated sample was weighed submerged in water; this was accomplished by suspending a wire basket in a bucket of water from the underside of a Mettler P1210 balance. Knowing the specific gravity of the wax, 0.80, the bulk volume of the sample was calculated using Archimedes Principle.

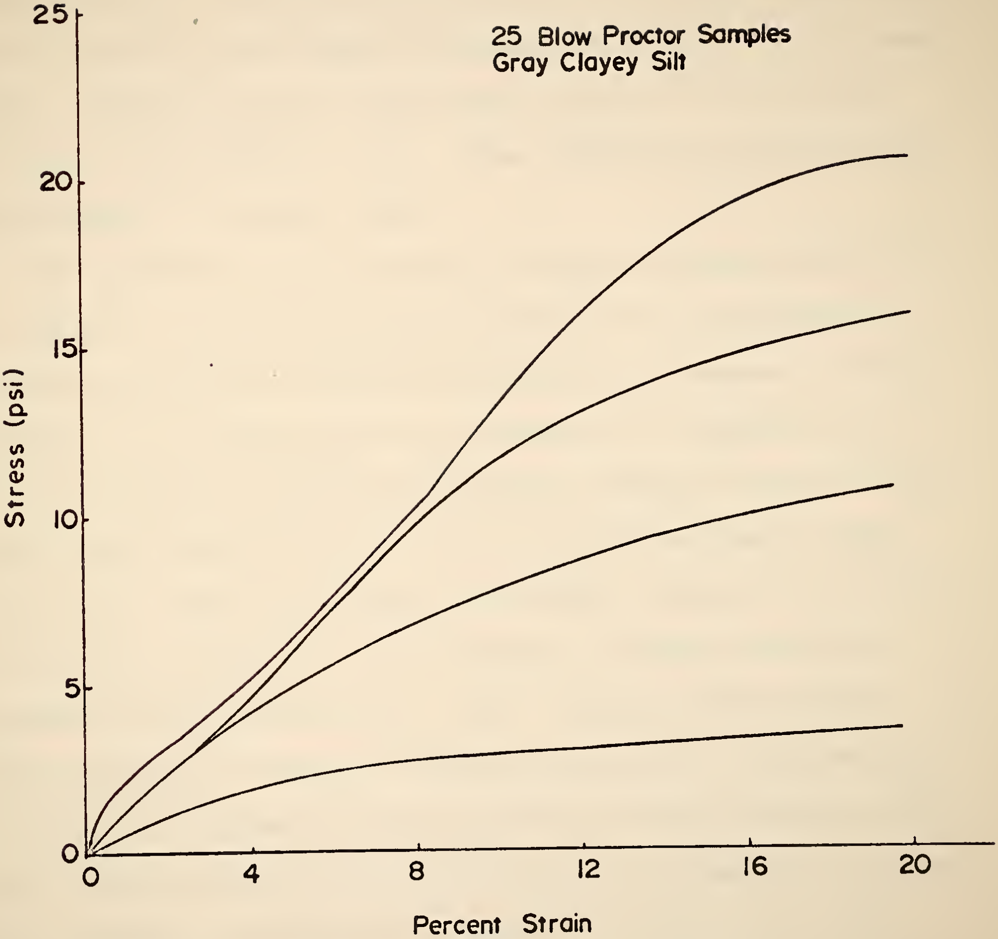

FIGURE 5 TYPICAL SOAKED STRESS-STRAIN CURVES.

The wax was then peeled off the sample and a final water content determination made. The final void ratio was calculated knowing the total weight, the total volume, the water content, and the specific gravity of solids. Once the final void ratio was known the degree of saturation was computed. Determining the final void ratio was a very time-consuming and difficult task. This difficulty had also been experienced by Leonards (1955).

The difficulties in obtaining accurate measurements of the sample volume and specific gravity of solids yielded numerous calculated degrees of saturation in excess of 100%. However, the distribution of the degrees of saturation for all 117 laboratory compacted specimens tested yielded a mean, median, and mode of 99.8%, 100.7%, and 100.6% respectively. Seed et al. (1954), Seed and Chan (1961), Fredlund and Dahlman (1972), and Bhasin (1975) present soil data in which degrees of saturation exceed 100%. Fredlund and Dahlman (1972) explained this was caused by inaccurate measurements of sample dimensions and the use of an assumed specific gravity. Bhasin (1975) measured the degree of saturation for impact compacted specimens of Grundite ($w_L = 56\%$, $w_p = 32\%$) that had been soaked under a surcharge pressure of 3/4 psi. Values in excess of 100% were believed to have been caused by nonuniform water contents.

# ANALYSIS OF EXPERIMENTAL RESULTS

## Statistical Analysis

A total of 117 samples were tested for soaked strength in this part of Phase II of the laboratory testing program. The samples were all laboratory impact compacted. All data obtained for this report are presented in the Appendix A.

The statistical analysis performed on the soaked data was similar to that presented by Essigmann (1976). The method of analysis depended on whether the actual magnitude of the dependent variable or the magnitude of its variation was under examination. If the actual magnitude was under examination, all the data obtained were used in the analysis. If the magnitude of the variability was under examination, the data were divided into subsets and the statistical analysis was performed using this reduced set of data. The subsets were obtained by dividing data into 1% water content intervals with respect to the optimum water content for the particular energy level under consideration. Means and variances were calculated within each subset using a Purdue computer program titled DATASUM.

To examine and isolate the effects of independent variables on a chosen response or dependent variable, the method of least squares was used to examine the data and to draw meaningful conclusions about dependency relationships that

may exist. This method of analysis is usually referred to as regression analysis.

Suppose one wishes to examine the way in which a response Y depends on an independent variable X. Assume that for simplicity the relationship can be written as a linear, first-order model. Then, the model becomes

$$Y_i = \beta_o + \beta_1 X_i + \varepsilon_i$$

where for a given $X_i$, a corresponding observation $Y_i$ consists of the value $\beta_o + \beta_1 X_i$ plus an amount $\varepsilon_i$, the departure from the regression line (also called random error). $\beta_o$ and $\beta_1$ and called the parameters of the model.

For the least squares criterion it is useful to minimize the sum of the square of errors. The sum of the square of errors may be written as

$$S = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} (Y_i - \beta_o - \beta_i X_i)^2$$

Then we choose estimates $b_o$ and $b_1$ to be values which, when substituted for $\beta_o$ and $\beta_1$, produce the least possible value of S. The estimated regression equation then becomes

$$\hat{Y} = b_o + b_1 X$$

where $\hat{Y}$ is an estimate of the dependent variable.

A measure of the usefulness of the terms in a linear regression model is the coefficient of determination, $R^2$, which is defined as

$$R^2 = \frac{\text{Sum of squares due to regression}}{\text{Total (corrected) sum of squares}}$$

$$= \frac{(\hat{Y}_i - \bar{Y})^2}{(Y_i - \bar{Y})^2}$$

It is often expressed as a percentage, $100R^2$. The coefficient of determination is the percent variation explained by the regression line. The larger $R^2$ is the better the fitted equation explains the variation in the data. If the model is deterministic, i.e., no random error, then $R^2$ is unity and all variation is explained by the regression equation. An $R^2$ value of zero indicates that no variation is explained by the model.

There is no unique statistical procedure for selecting the "best" regression equation. No two procedures will necessarily lead to the same regression equation when applied to the same set of data. Personal judgment thus becomes a necessary part in any of the procedures. Procedures currently used today are (1) all-possible regressions, (2) backward elimination, (3) forward selection, (4) stepwise regression, and (5) stagewise regression. Draper and Smith (1966) provide an excellent summary and discussion of each of these procedures.

Because access to a high-speed computer was available, the "all-possible" regressions procedure was used to help select possible "best" models. The all-regressions procedure enabled all possibilities and combinations of independent variables to be looked at. Different independent variables, including their squares, cubes, cross products, and

combinations were examined by this procedure. The regressions were divided up into sets of runs which involve p variables, p = 1, 2, .... k, and each set was ordered according to the criterion of the maximum $R^2$ values achieved by the least squares fit. The Purdue computer program DRRSQU was used for this phase of the statistical analysis and yielded an ordered listing, from high to low $R^2$ values, of possible models.

Opponents of the all-possible regressions procedure say that it is sometimes unwarranted. They feel that the amount of computer time is excessive and that many of the regression equations can be eliminated by hand using intelligent thought. Although the above is true, it was felt that the all-possible regression procedure provided a systematic method of examining the various models.

Once the "best" models were isolated, prediction equations were developed using the SPSS (Statistical Package for the Social Sciences) computer program REGRESSION developed by Nie et al. (1975). The prediction equations were then examined as to their adequacy and usefulness. The criteria used were (1) the coefficient of determination, $R^2$, (2) the overall F-test for significance of regression, (3) the partial F-test for each $\beta_i$ (regression coefficient), and (4) the 95% confidence limits ($\alpha = 0.05$) for each $\beta_i$. Prediction equations developed were considered of value if they had a high $R^2$ value, the overall F-test was significant at $\alpha = 0.05$, the

partial F-test for each regression coefficient was significant at $\alpha = 0.05$, and the 95% confidence limits for the coefficients were small and did not cross zero. Draper and Smith (1966) and Ostle and Mensing (1975) in their texts provide discussions concerning the above criteria.

An inherent assumption in the least square regression analysis is that the residuals, i.e., differences between the observed and corresponding predicted values, follow certain assumptions. The errors are assumed to be independent normally distributed random variables with mean zero and constant variance. In order for a fitted regression equation to be valid, an examination of the residuals should be made (Scott, 1976). Figure 6 gives the plots of the soaked strength residuals versus molding water content for specimens compacted dry of optimum. The shape of the plots are conical which indicates that the subpopulation variances are not constant. Because of this, Goel (1977) suggested that the regression models be adjusted by the Iterative Least Square Procedure (Searle, 1977). Although the models developed during this research can be used, the Iterative Least Square Procedures would have provided some improvement in the reliability of the models. Future researchers are encouraged to investigate the improvement in reliability resulting from this procedure.

If the residuals are normally distributed, then 95% of the observed residuals should lie within ± two standard deviations

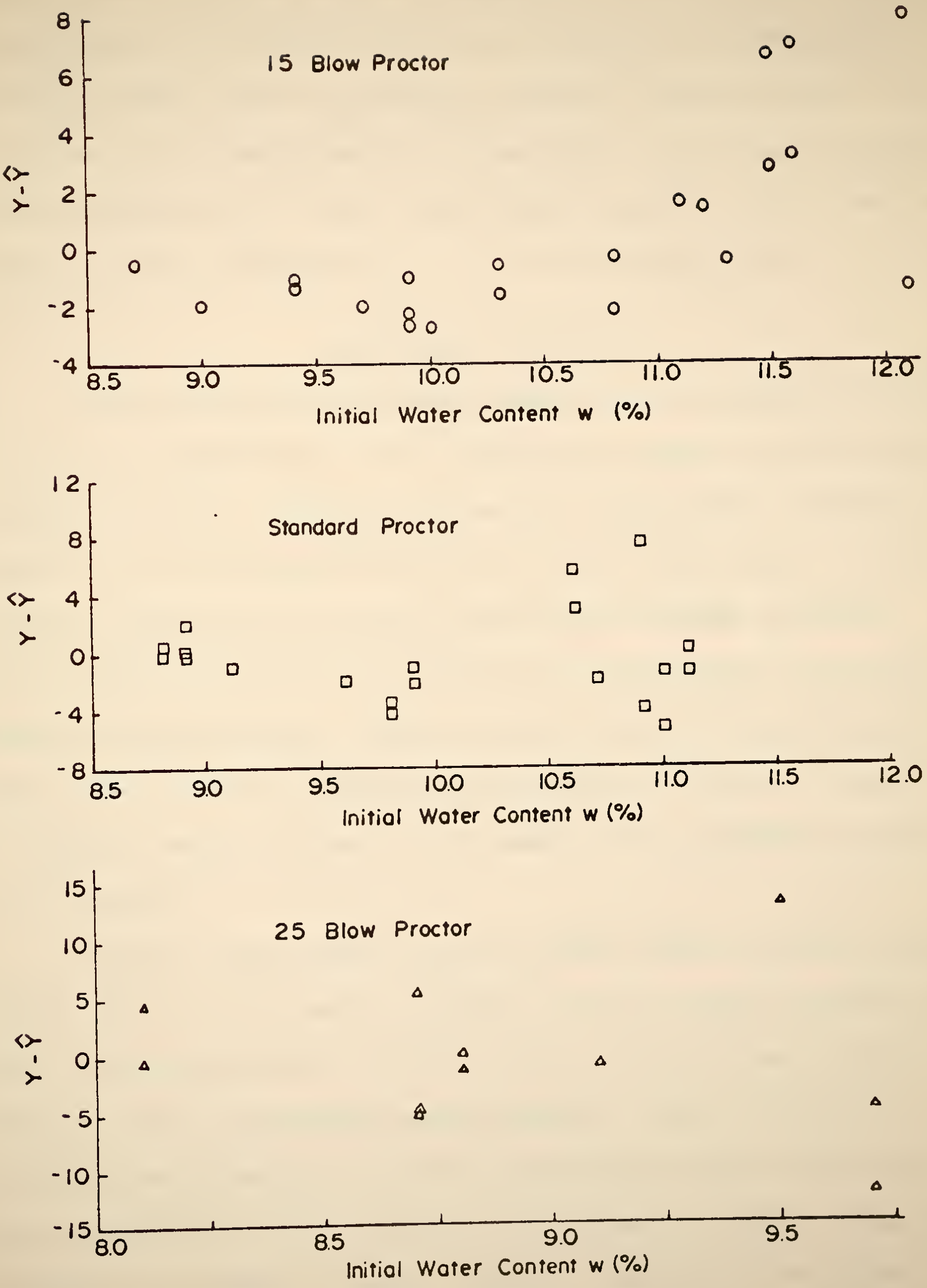

FIGURE 6 RESIDUAL PLOTS FOR SOAKED STRENGTH DRY OF OPTIMUM.

($\pm$ 2$\sigma$) when plotted versus frequency of occurrence. This assumption was checked using the output of the REGRESSION program which gave the percent residuals lying outside $\pm$ 2$\sigma$. For the prediction equations developed, the number of residuals outside of $\pm$ 2$\sigma$ was always less than 7%, except for one case in which the number of $\pm$ 2$\sigma$ outliers was 11%.

## Statistical Results

The independent variables used in the statistical analysis of the magnitude of dry density and soaked strength are shown in Table 3. Table 4 shows the independent variables used in the statistical analysis of the magnitude of variability associated with dry density and soaked strength. Both tables show only the first order independent variables used in the analysis. Squares and cubes of these variables were also used as independent variables. Thus, for example w (molding water content), was used in the analyses as well as $w^2$ and $w^3$.

The data were broken up into three water content ranges. These were (1) all water contents, (2) all water contents less than the optimum water content, and (3) all water contents greater than the optimum water content. The all-possible regressions procedure was then performed on the magnitude and variability of dry density and soaked strength using the three water content ranges. Tables 5 through 8 show the "best" models obtained from the statistical analyses. If the coefficient of determination, $R^2$, for each of the resulting

Table 3. Statistical Models Used for Magnitude Analysis

| Dependent Variable | Independent Variables Used In Analysis | | | | | |
|---|---|---|---|---|---|---|
| | $w$ | $\gamma_d$ | $E$ | $wE$ | $\gamma_d E$ | $w\gamma_d$ |
| Dry Density | X | | X | X | | |
| Soaked Strength | X | X | X | X | X | X |

models was greater than 50%, the models were considered of value.

The results of the all-possible regressions were then used to obtain prediction equations. These prediction (or regression equations) were established by the method of least squares. Table 9 shows the results of the density, variation in density, soaked strength, and variation in soaked strength relationships. These regression relationships were developed from models with the lowest order and lowest number of independent variables meeting the significance criteria. When all criteria were met by more than one model, the model with the lowest number of variables was used provided higher variables models did not appreciably increase the percent variation explained ($R^2$).

Table 4. Statistical Models Used for Variability Analysis

| Dependent Variable | Independent Variables Used in Analsysis | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\overline{w}$ | $\overline{\gamma}_d$ | $\overline{q}_u$ | E | $\overline{wE}$ | $\overline{\gamma}_dE$ | $\overline{w\gamma_d}$ | $\overline{wq_u}^s$ | $s(\gamma_d)$ | $s(\gamma_d)E$ |
| Variation in Dry Density | X | X | | X | X | X | X | | | |
| Variation in Soaked Strength | X | X | X | X | X | X | X | X | X | X |

Table 5. All-Possible Regression Models for Dry Density

| Moisture Range | Independent Variables and % Variation Explained | | | |
|---|---|---|---|---|
| | One Variable Model | Two Variable Model | Three Variable Model | Four Variable Model |
| All Moistures | * | * | * | $w, w^2, WE, E$ 65.7<br>$w, w^3, WE, E$ 65.6<br>$w^2, w^3, WE, E$ 65.4 |
| Dry of Optimum | * | $w, E$ 81.1<br>$w^2, E$ 80.3<br>$w, wE$ 80.2 | ** | ** |
| Wet of Optimum | * | * | $wE, E, w^2E^2$ 51.9<br>$w, E, E^3$ 51.0<br>$w, E, E^2$ 51.0<br>$w, E^2, E^3$ 51.0 | ** |

* No models meet significance criteria; i.e., $R^2 < 50\%$.

** Higher variable models do not appreciably increase % variation explained.

Table 6. All-Possible Regression Models for Variation in Dry Density

| Moisture Range | Independent Variables and % Variation Explained | | | | | |
|---|---|---|---|---|---|---|
| | One Variable Model | Two Variable Model | Three Variable Model | | Four Variable Model | |
| All Moistures | * | * | * | | * | |
| Dry of Optimum | * | * | $\bar{w}$, $\overline{w\gamma_d}$, $\bar{\gamma}_d^3$ | 68.6 | $\bar{w}$, $\overline{w\gamma_d}$, $\bar{w}^2$, $\bar{\gamma}_d^3$ | 77.7 |
| | | | $\bar{w}$, $\overline{w\gamma_d}$, $\bar{\gamma}_d^2$ | 65.5 | $\bar{w}$, $\bar{w}^2$, $\overline{w\gamma_d}$, E | 77.5 |
| | | | | | $\bar{w}$, $\bar{w}^2$, $\overline{w\gamma_d}$, $\bar{\gamma}_dE$ | 77.3 |
| | | | | | $\bar{w}$, $\bar{w}^3$, $\overline{w\gamma_d}$, $\bar{\gamma}_d^3$ | 76.9 |
| | | | | | $\bar{w}$, $\bar{w}^3$, $\overline{w\gamma_d}$, E | 76.7 |
| Wet of Optimum | * | * | E, $E^3$, $\bar{\gamma}_dE$ | 51.9 | E, $E^3$, $\overline{wE}$, $\bar{\gamma}_dE$ | 78.8 |
| | | | E, $E^2$, $\bar{\gamma}_dE$ | 51.9 | E, $E^2$, $\overline{wE}$, $\bar{\gamma}_dE$ | 78.8 |
| | | | $E^2$, $E^3$, $\bar{\gamma}_dE$ | 51.9 | $E^2$, $E^3$, $\overline{wE}$, $\bar{\gamma}_dE$ | 78.8 |

* No models meet significance criteria; i.e., $R^2 < 50\%$.

Table 7. All-Possible Regression Models for Soaked Strength

| Moisture Range | Independent Variables and % Variation Explained | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | One Variable Model | | Two Variable Model | | Three Variable Model | | Four Variable Model | |
| All Moistures | * | | * | | * | | $w, \gamma_d^2, \gamma_d^3, w^2\gamma_d^2$ | 55.3 |
| | | | | | | | $w, \gamma_d, \gamma_d^3, w^2\gamma_d^2$ | 55.1 |
| | | | | | | | $w, \gamma_d, \gamma_d^2, w^2\gamma_d^2$ | 54.9 |
| | | | | | | | $w, w^2, w^2E^2, \gamma_d^2E^2$ | 53.2 |
| Dry of Optimum | * | | $w^2E^2, E^2$ | 65.7 | $w^2E^2, E^2, \gamma_d^2E^2$ | 71.5 | ** | |
| | | | $E^2, \gamma_d^2E^2$ | 63.3 | $w^2E^2, E, \gamma_dE$ | 68.5 | | |
| | | | $w^2E^2, E$ | 63.0 | $E^2, w^2E^2, w^2\gamma_d^2$ | 68.2 | | |
| | | | $wE, E$ | 62.1 | $w^3, w^2E^2, E^2$ | 68.0 | | |
| | | | $\gamma_d^2, \gamma_d^3$ | 61.6 | $E^2, w\gamma_d, w^2E^2$ | 68.0 | | |
| | | | $\gamma_d, \gamma_d^3$ | 61.2 | $E^2, wE, \gamma_d^2E^2$ | 68.0 | | |
| Wet of Optimum | $w$ | 60.5 | $w^2, w^3$ | 63.5 | $w, \gamma_d, w\gamma_d$ | 65.6 | ** | |
| | $w^2$ | 59.1 | $w, w^3$ | 63.5 | $w, w\gamma_d, \gamma_d^2$ | 65.3 | | |
| | $w\gamma_d$ | 58.7 | $w, w^2$ | 63.5 | $w^2, \gamma_d, w^2\gamma_d^2$ | 65.2 | | |
| | $w^2\gamma_d^2$ | 57.8 | $w\gamma_d, \gamma_d^3$ | 61.4 | $w^3, \gamma_d^3, w^2\gamma_d^2$ | 65.1 | | |
| | $w^3$ | 57.5 | $w, E\gamma_d$ | 61.3 | | | | |
| | | | $w, E$ | 61.3 | | | | |

Table 8. All-Possible Regression Models for Variation in Soaked Strength

| Moisture Range | Independent Variables and % Variation Explained | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | One Variable Model | | Two Variable Model | | Three Variable Model | | Four Variable Model | |
| All Moistures | $\bar{q}_u^{s^2}$ | 89.0 | $\bar{q}_u^{s}, \overline{wq}_u^{s}$ | 91.1 | | | | |
| | $\bar{q}_u^{s}$ | 85.5 | $\bar{q}_u^{s^2}, \bar{\gamma}_d^{3}$ | 91.0 | ** | | ** | |
| | $\overline{wq}_u^{s}$ | 75.1 | $\bar{q}_u^{s^2}, \bar{\gamma}_d^{2}$ | 90.0 | | | | |
| | | | $\bar{q}_u^{s^2}, \bar{\gamma}_d$ | 90.5 | | | | |
| Dry of Optimum | $\bar{q}_u^{s^2}$ | 97.9 | $\bar{q}_u^{s}, \bar{q}_u^{s^2}$ | 99.5 | | | | |
| | $\bar{q}_u^{s}$ | 97.7 | $\bar{q}_u^{s}, \overline{w\gamma}_d$ | 99.3 | ** | | ** | |
| | $\overline{wq}_u^{s}$ | 94.1 | $\bar{q}_u^{s}, \overline{wq}_u$ | 99.3 | | | | |
| | | | $\bar{q}_u^{s}, \bar{w}^3$ | 99.2 | | | | |
| Wet of Optimum | $\overline{wq}_u^{s}$ | 80.1 | $\overline{wq}_u^{s}, \bar{\gamma}_d^{2}$ | 82.3 | | | | |
| | $\bar{q}_u^{s}$ | 78.5 | $\overline{wq}_u^{s}, \bar{\gamma}_d$ | 82.2 | $E, E^3, \bar{\gamma}_d E$ | 90.4 | $\bar{q}_u^{2}, E, E^3, \bar{\gamma}_d E$ | 96.4 |
| | $\bar{q}_u^{s^2}$ | 73.2 | $\overline{wq}_u^{s}, \overline{w\gamma}_d$ | 81.7 | $E, E^2, \bar{\gamma}_d E$ | 90.4 | $\bar{q}_u^{2}, E, E^2, \bar{\gamma}_d E$ | 96.4 |
| | $\bar{w}$ | 72.1 | $\overline{wq}_u^{s}, E^3$ | 80.9 | $E^2, E^3, \bar{\gamma}_d E$ | 90.4 | $\bar{q}_u^{2}, E^2, E^3, \bar{\gamma}_d E$ | 96.4 |
| | $\bar{w}^2$ | 71.9 | $\overline{wq}_u^{s}, E^2$ | 80.8 | | | | |
| | $\bar{w}^3$ | 71.3 | | | | | | |

Table 9. Regression Results

| Dependent Variable | Moisture Range | Regression Relationship | $R^2$ |
|---|---|---|---|
| Dry | All Moistures | $\gamma_d = 17.257w-0.671w^2+9.962E-0.774wE+10.85$ | 0.657 |
| Density | Dry of Optimum | $\gamma_d = 3.253w+3.334E+81.84$ | 0.811 |
| | Wet of Optimum | $\gamma_d = 6.60E-1.099wE+0.00821w^2E^2+128.79$ | 0.519 |
| Variation in | All Moistures | No Models Significant. | -- |
| Dry Density | Dry of Optimum | $S(\gamma_d) = 24.668\bar{w}-0.202\overline{w\gamma}_d+0.0000405\bar{\gamma}_d{}^3-72.89$ | 0.686 |
| | Wet of Optimum | $S(\gamma_d) = 51.386E+0.168E^3-0.351\overline{w}E-0.416\bar{\gamma}_dE+5.682$ | 0.788 |
| Soaked | All Moistures | $q_u{}^s = 26.184w-0.178\gamma_d{}^2+0.00106\gamma_d{}^3-0.000078w^2\gamma_d{}^2$<br>$+591.79$ | 0.553 |
| Strength | Dry of Optimum | $q_u{}^s = -13.19E^2+0.000679\gamma_d{}^2E^2+0.0385w^2E^2+3.53$ | 0.715 |
| | Wet of Optimum | $q_u{}^s = -4.71w+69.427$ | 0.605 |
| Variation in | All Moistures | $S(q_u{}^s) = 1.293\bar{q}_u{}^s-0.0753\overline{wq}_{u_2}{}^s-0.218$ | 0.911 |
| Soaked | Dry of Optimum | $S(q_u{}^s) = 0.307\bar{q}_u{}^s+0.0113\bar{q}_{u_2}{}^s+0.36$ | 0.995 |
| Strength | Wet of Optimum | $S(q_u{}^s) = -.67.104E-1.859E^2+0.634\bar{\gamma}_dE-7.229$ | 0.904 |

# DISCUSSION OF RESULTS

## Magnitude of Soaked Strength

It was shown in Table 9 that the magnitude of the soaked strength can best be described by considering independently all water contents less than the optimum water content and all water contents greater than the optimum water content. For compaction dry of optimum, the magnitude of soaked strength is described by the energy level, the interaction of dry density and energy, and the interaction of water content and energy. The magnitude of the soaked strength compacted wet of optimum is controlled only by the molding water content. Figure 7 shows the soaked strength regression relationships for specimens compacted both dry and wet of optimum. The regression relationships are shown by the lines while the points represent the average values of the 1% water content intervals.

The prediction equations fit the data quite well except for the lowest energy level (15 Blow Proctor). The maximum soaked strength for the two lowest energy levels occurs at a moisture content slightly larger than their respective optimum water content. The maximum soaked strength for the highest energy level (25 Blow Proctor) occurs at a water content about 1% drier than the optimum water content. Thus for all

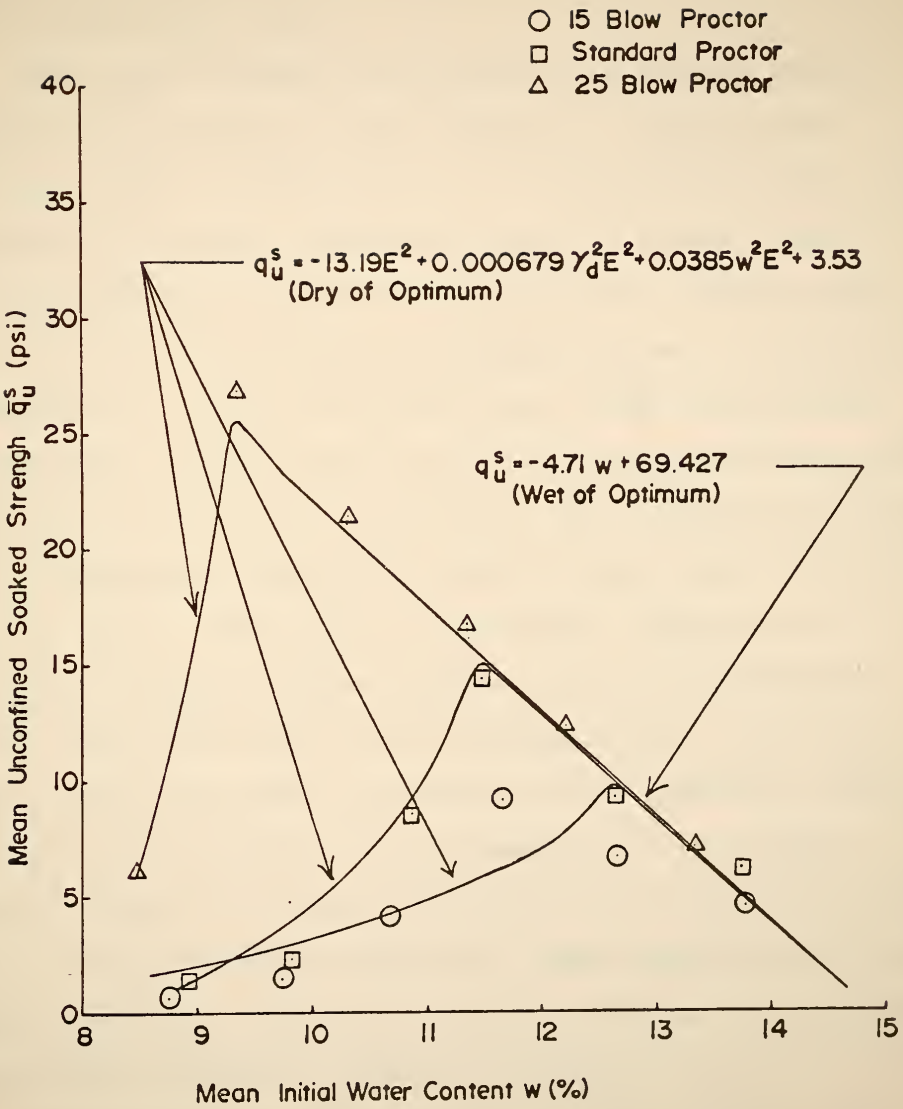

FIGURE 7 MOISTURE-SOAKED STRENGTH REGRESSION RELATIONSHIPS FOR LABORATORY COMPACTION.

[illegible]

three energy levels studied, the maximum soaked strength was obtained within ±1% of the optimum water content for the particular energy level.

The soaked strength decreases as the molding water content moves away to either side of the optimum water content. This was observed for all three energy levels. In addition, all energy levels show that the soaked strength decreases much more rapidly on the dry side of optimum than on the wet side. This probably occurred because the specimens compacted dry of optimum had more air voids and therefore experienced a greater water content change when soaked than specimens compacted wet of optimum. The specimens compacted wet of optimum had fewer air voids and thus could not absorb as much water. Therefore, the specimens compacted wet of optimum softened less upon soaking. Turnbull and Foster (1956) developed soaked CBR relationships for a lean clay, ML-CL. They concluded that soaking tests produced a large reduction in the CBR of soils compacted dry of optimum, a smaller change for those compacted at the optimum water content, and only a slight change for those compacted on the wet side of optimum. The results of this research are consistent with those obtained by Turnbull and Foster (1956).

The regression relationship for soaked strength compacted dry of optimum indicates that for a given energy, the strength will increase as the dry density increases. Also, the regression relationship indicates that an increase in

strength occurs as the water content increases for specimens compacted dry of optimum.

The regression relationship for soaked strength compacted wet of optimum indicates that the strength decreases linearly as the molding water content increases. This relationship is less complex, contains fewer variables, than the relationship for specimens compacted dry of optimum. Specimens compacted dry of optimum tend to have greater swelling tendencies than those compacted wet of optimum (Seed et al. 1960). Although swelling was not measured during this research, these swelling tendencies probably resulted in the magnitude of soaked strength for specimens compacted dry of optimum to be more complex.

## Magnitude of Soaked Strength Variability

The variation in soaked strength can be described by a single relationship for the entire range of water contents used in this investigation. Table 9 shows the resulting regression relationship for the variability of soaked strength. The relationship involves the magnitude of the soaked strength and the interaction of the water content and soaked strength. Relationships which met the statistical acceptance criteria were also developed for moisture ranges dry and wet of the optimum water content. However, these relationships were either of higher order or contained more terms than the two term model for all water contents. This two-term model was

therefore believed to be more efficient and certainly no more costly in terms of the number of predictor variables.

Figure 8 shows the developed variation in soaked strength regression relationship. The regression relationship is shown by the lines while the points represent the values for the 1% moisture content intervals. The largest variation in soaked strength for all three energy levels occurs at a molding water content within ± 1/2% of the optimum water content for the particular effort level. This result is quite reasonable since the maximum soaked strength discussed earlier was obtained at a molding water content within ± 1% of the optimum water content for the particular effort level. Thus, one can expect that the in-service strength of a compacted soil prepared in the laboratory will have the highest variation when compacted near the optimum water content. If field and laboratory soaked strength relationships prove to be similar, then the designer can expect to obtain the highest variability of in-service strength for soils compacted near the field optimum water content.

An examination of the regression relationship for variation in soaked strength indicates that for a given molding water content, an increase in the magnitude of soaked strength results in an increase in the variability of soaked strength. Figure 8 shows the variation in soaked strength increases as the compactive effort increases for a given molding water content. The effort level with the highest

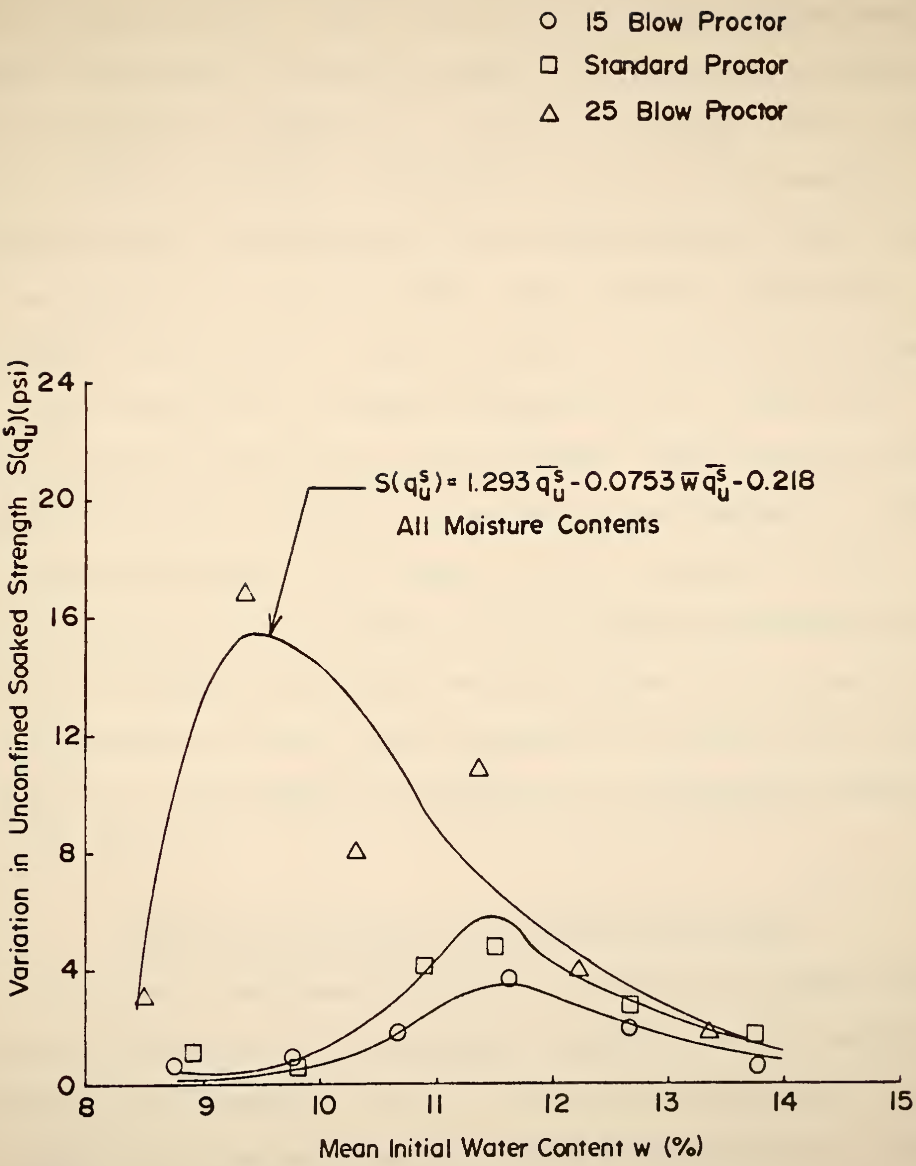

FIGURE 8 MOISTURE-VARIATION IN SOAKED STRENGTH RELATIONSHIPS FOR LABORATORY COMPACTION.

variation in soaked strength at its optimum water content was the 25 Blow Proctor. The 25 Blow Proctor also yielded much larger variations in soaked strength for specimens compacted dry of optimum as compared to the two low energy levels. On the wet side of optimum, differences in the magnitude of soaked strength variability for the three energy levels are not as large as on the dry side. As a matter of fact, for specimens compacted at a water content of about 12% or greater, the variability of soaked strength for all three compactive efforts are quite similar indeed. The variation in soaked strength is smaller for molding water contents on the wet side of optimum. The reason for this is that all the initial degrees of saturation are high and approximately the same for specimens compacted wet of optimum. This results in the imbibition of water during soaking to be less than that for the dry side compacted specimens and subsequent swelling also to be less.

## Comparison of Soaked and Unsoaked Strength

The most significant difference between the soaked and unsoaked strengths is the strength reduction of the compacted specimens upon soaking. Figure 9 shows the magnitude of the as-compacted (unsoaked) strength obtained by Essigmann (1976) and the soaked strength plotted against molding water content. The soaked strength is less than the as-compacted strength for each respective energy level.

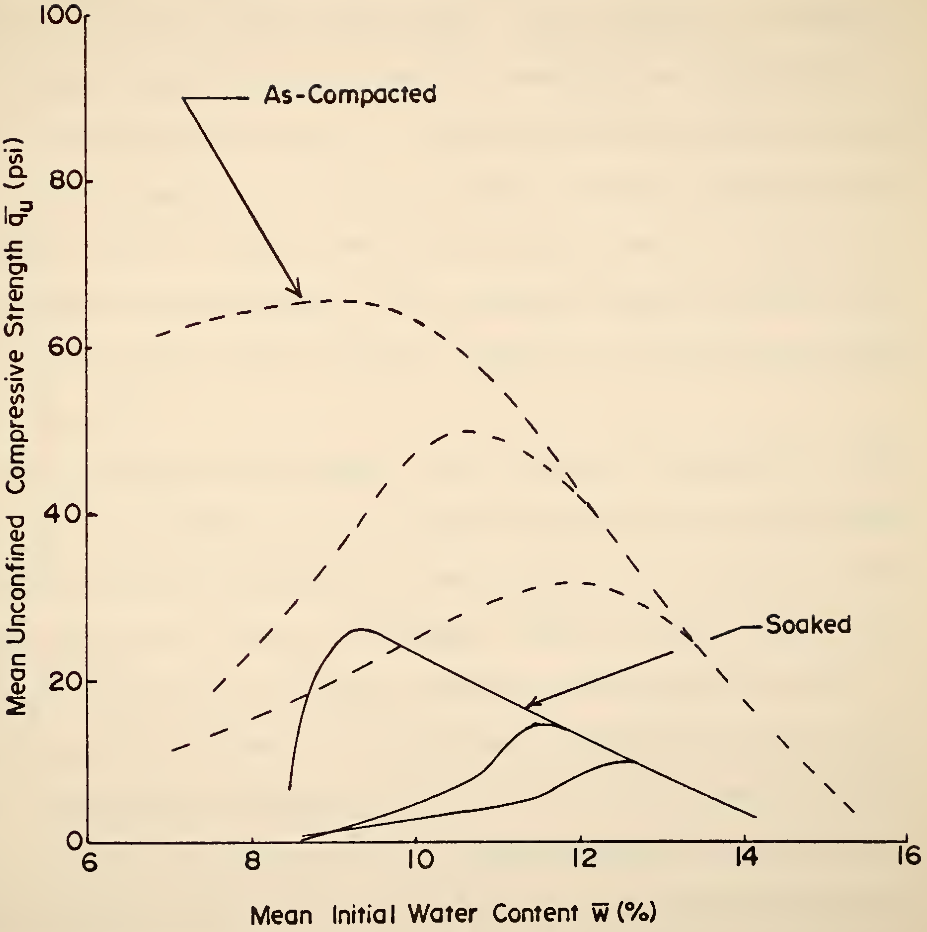

FIGURE 9 COMPARISON OF SOAKED AND UNSOAKED STRENGTH REGRESSION RELATIONSHIPS.

For the as-compacted specimens, the strength is higher on the dry side of the optimum water content. The maximum as-compacted strength for any laboratory energy level occurs at a water content about 1% drier than the optimum water content. For the soaked specimens, the strength is higher on the wet side of optimum because swelling was permitted during the soaking process. A high undrained soaked strength for clays compacted on the wet side of optimum was observed by Lambe (1960) if free swelling, or even partial swelling is allowed during soaking. The maximum soaked strength was obtained within a water content range of ± 1% of the optimum water content.

Both studies, Essigmann (1976) and this research, indicate that the soaked and unsoaked strengths can be expressed as functions of the molding water content for specimens compacted on the wet side of optimum. These studies show that both the soaked and unsoaked strengths decrease with increasing water contents for specimens compacted on the wet side. Specimens compacted wet of optimum have densities and water contents corresponding to high degrees of saturation. These results are encouraging since in soil mechanics there is a well-established principal that the strength of saturated clays decreases with increasing water content.

The regression results for the as-compacted specimens indicate that the magnitude of the unsoaked strength can be described with a relationship consisting of the dry density

and the interaction between dry density and water content for all ranges of moisture content considered (Essigmann, 1976). For a constant dry density, increasing the water content will decrease the as-compacted strength. Increasing the dry density at a constant water content will generally increase the as-compacted strength. The regression results for the soaked specimens were discussed previously in this report.

In discussing the laboratory testing for earth dam design used by the Waterways Experiment Station, Johnson (1950) describes the testing of laboratory compacted specimens used to simulate as-compacted and in-service conditions. Impact compacted specimens were saturated and consolidated-quick tests (undrained) conducted on them. Saturation was obtained by subjecting the specimens to a vacuum less than the consolidation pressure and allowing them to take on water. In general, these tests were performed on groups of specimens compacted at different compactive efforts. Families of curves were then constructed to show relationships between compactive effort, water content, dry density, and shear strength. Johnson (1950) presents shear strength data for a compacted clayey sand ($w_L = 20\%$, $w_p = 15\%$) obtained from quick (unconsolidated undrained) and consolidated-quick tests. The compaction curves for the clayey sand are shown in Figure 10 and the strength curves are plotted in Figures 11 and 12. The shear strength for the quick triaxial results, simulating the as-compacted condition, are high for water

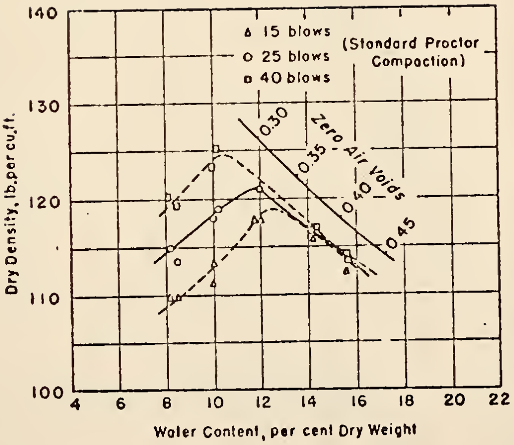

FIGURE 10 COMPACTION CURVES FOR CLAYEY SAND (JOHNSON, 1950).

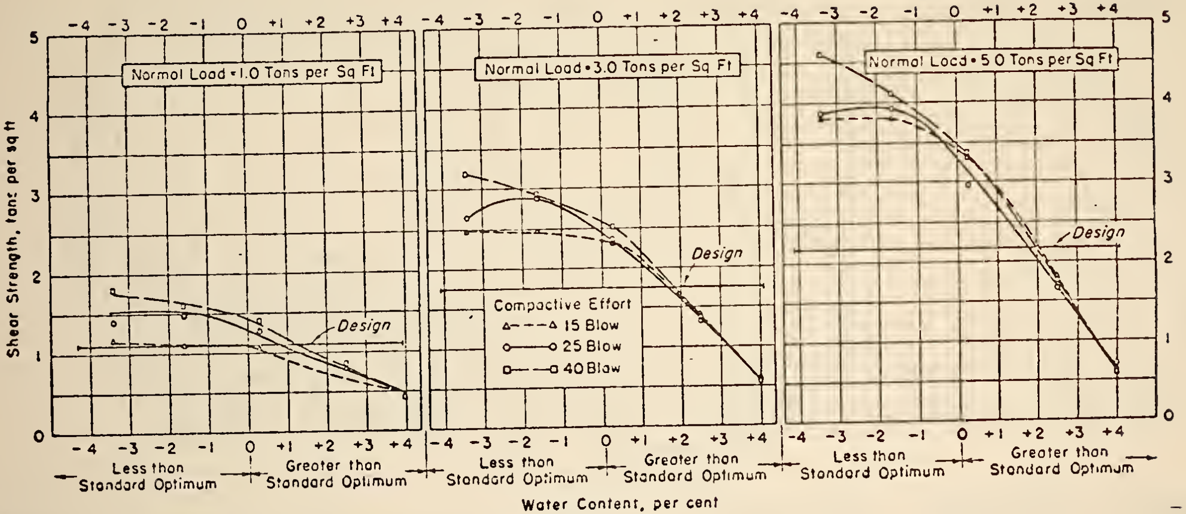

FIGURE 11 QUICK TRIAXIAL COMPRESSION TESTS FOR CLAYEY SAND (JOHNSON, 1950).

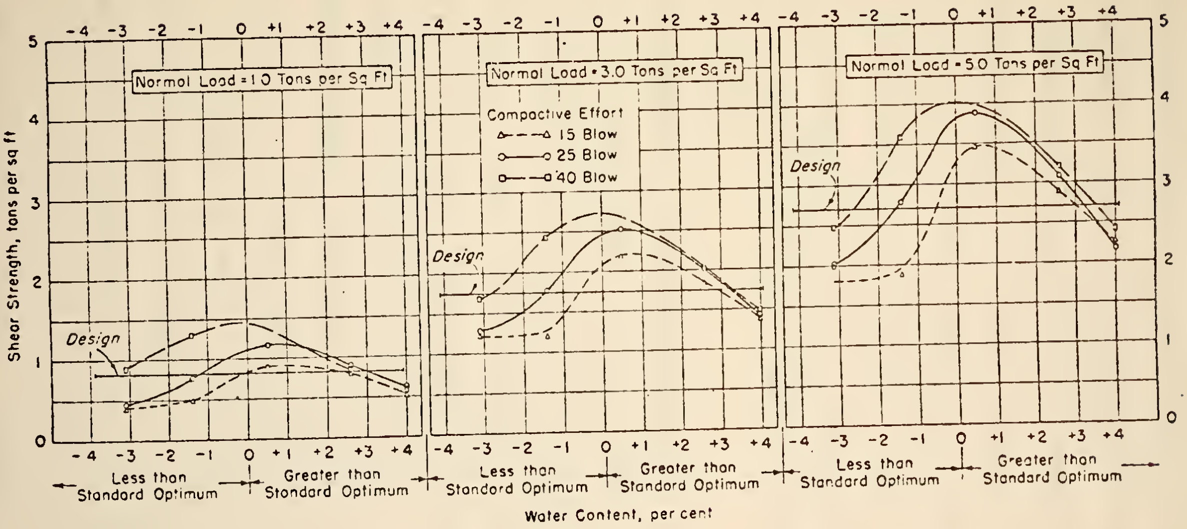

FIGURE 12 CONSOLIDATED-QUICK TRIAXIAL TESTS ON SATURATED CLAYEY SAND (JOHNSON, 1950).

contents less than optimum and decreases as the water content increases. The decrease was caused by pore water pressures resulting from the water content and degree of saturation increase. The consolidated-quick shear strength results, simulating a saturated in-service condition, are a maximum near the optimum water content and decreases for water contents both less and greater than optimum. The shapes of the families of curves, both with respect to water content and compactive effort, obtained for this research and Essigmann (1976) are quite similar to those developed by Johnson (1950).

The method of presenting data as in Figures 11 and 12 has several advantages. It eliminates the need for duplicate tests by making erratic test results readily apparent when plotted. Also, the influence of compactive effort can be clearly seen and savings may result by eliminating density requirements which may be too severe.

The Waterways Experiment Station (1949) performed an investigation to compare the soaked and unsoaked strength (CBR) of a compacted sand. Specimens were compacted according to the Modified AASHO, now AASHTO, procedure. The results of this study are shown in Figure 13. The as-compacted CBR increased with decreasing molding water content, while the soaked CBR reached a maximum at a water content slightly less than optimum. Wilson (1952) presents a comparison of soaked and unsoaked strength obtained from Harvard

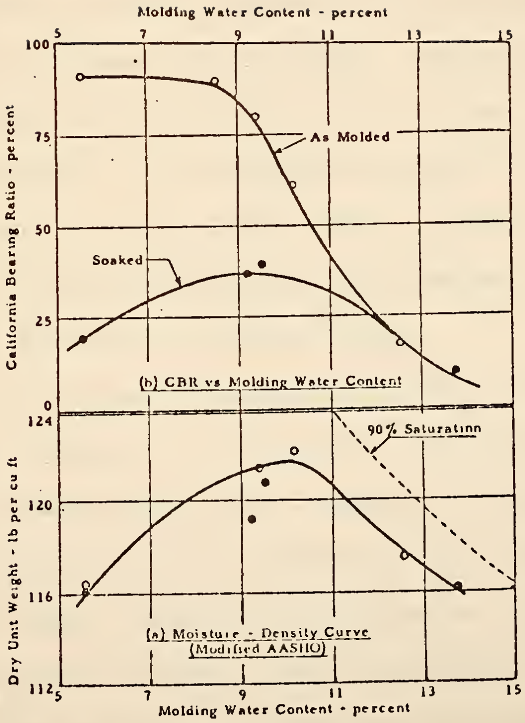

FIGURE 13 CBR RELATIONSHIPS FOR COMPACTED CLAYEY SAND (WES, 1949).

Miniature compacted specimens of the same clayey sand used by the Waterways Experiment Station (1949). Quick triaxial tests (Q tests) and unconfined compression tests (U tests) were used to represent as-compacted (unsoaked) strength and consolidated-quick ($Q_c$) tests on saturated specimens were performed to simulate in-service strength. The results of his investigation are shown in Figure 14a. It is clearly seen that the Q and U tests yielded no relationship between the optimum water content and strength. The as-compacted strength was higher dry of optimum and decreased with increasing water content. The maximum strength for the $Q_c$ tests was obtained at the optimum water content. A greater soaked strength reduction occurred for specimens compacted on the dry side compared to the wet side.

Stress-strain curves obtained by Wilson (1952) for the Q and $Q_c$ tests are shown in Figure 14b. It is interesting to note that although the $Q_c$ test specimens compacted dry of optimum had a greater strength reduction upon soaking, they also had a much higher modulus of deformation compared to those compacted wet of optimum. One can readily see "trade-offs" must be made between strength and deformation when preparing compaction specifications. These "trade-offs" will depend on the purpose and desired behavior of the compacted mass.

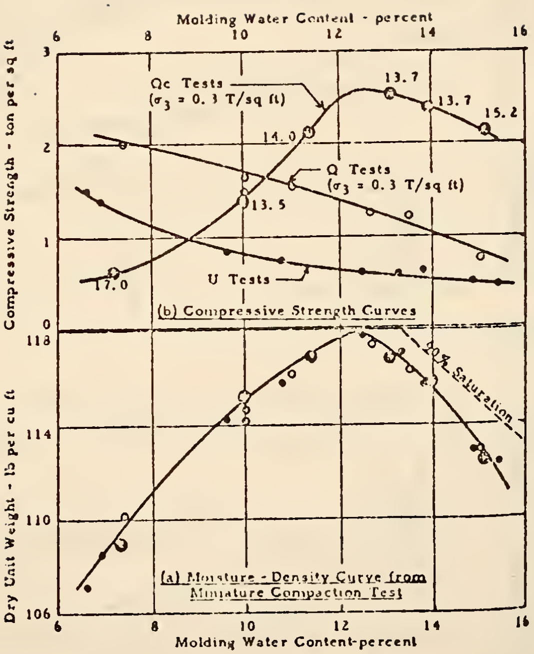

FIGURE 14a MOISTURE-STRENGTH RELATIONSHIPS FOR SOAKED AND UNSOAKED COMPACTED CLAYEY SAND (WILSON, 1952).

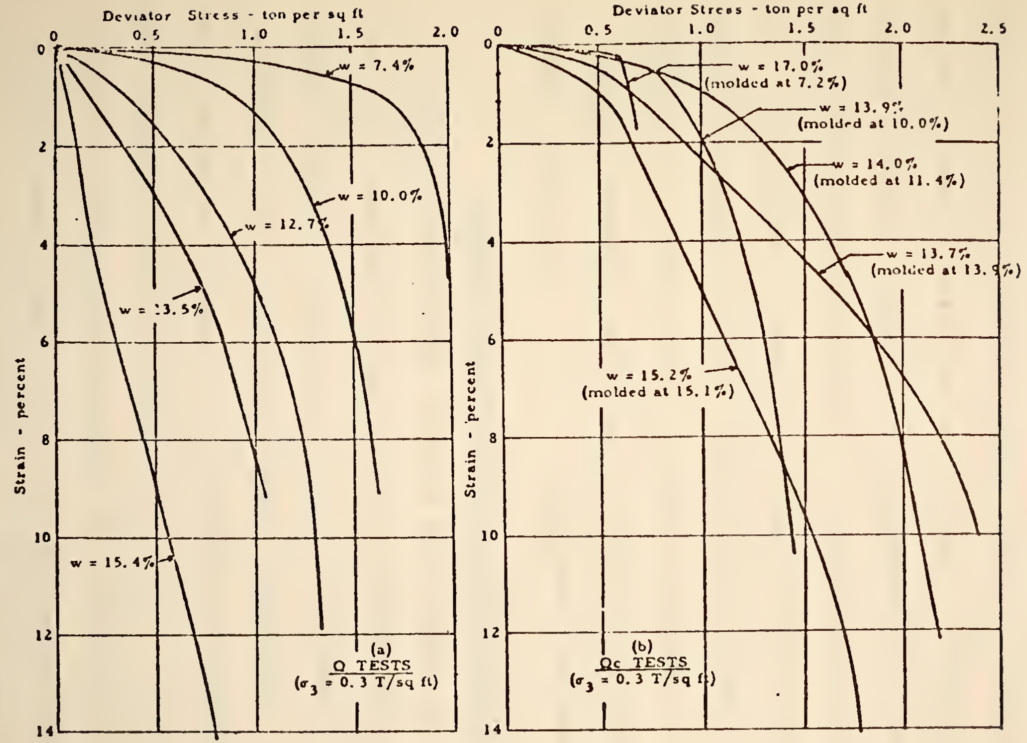

FIGURE 14b STRESS-STRAIN CURVES FOR SOAKED AND UNSOAKED COMPACTED CLAYEY SAND (WILSON, 1952).

## Comparison of Soaked and Unsoaked Strength Variability

Figure 15 gives a comparison of the soaked and unsoaked strength variability. To compare the soaked and unsoaked strength variation, the ratio of the variation in strength to the mean strength for a given water content interval is plotted. For all three energy levels, the variation of soaked strength relative to the mean soaked strength is larger than the variation of as-compacted strength to the mean as-compacted strength at a given water content interval. Therefore, although the magnitudes of the variation in soaked strength are less than the variation in as-compacted strength at a given water content interval, the variation in soaked strength relative to the mean soaked strength is greater than that of the as-compacted specimens.

## Water Content Change Upon Soaking

Figures 16 through 18 show the change in water content that occurred during the soaking process for the three energy levels. The points plotted represent the average values of the 1% moisture content intervals. The water content increase is due to saturation and swelling. The former was caused by water filling the voids in the sample and the latter by absorbtion of water by the sample during swelling.

It is easily seen that the specimens compacted dry of optimum experienced a larger change in water content upon soaking than those compacted wet of optimum. Since the strength of saturated clays is essentially dependent on void ratio (water content), the change in water content for

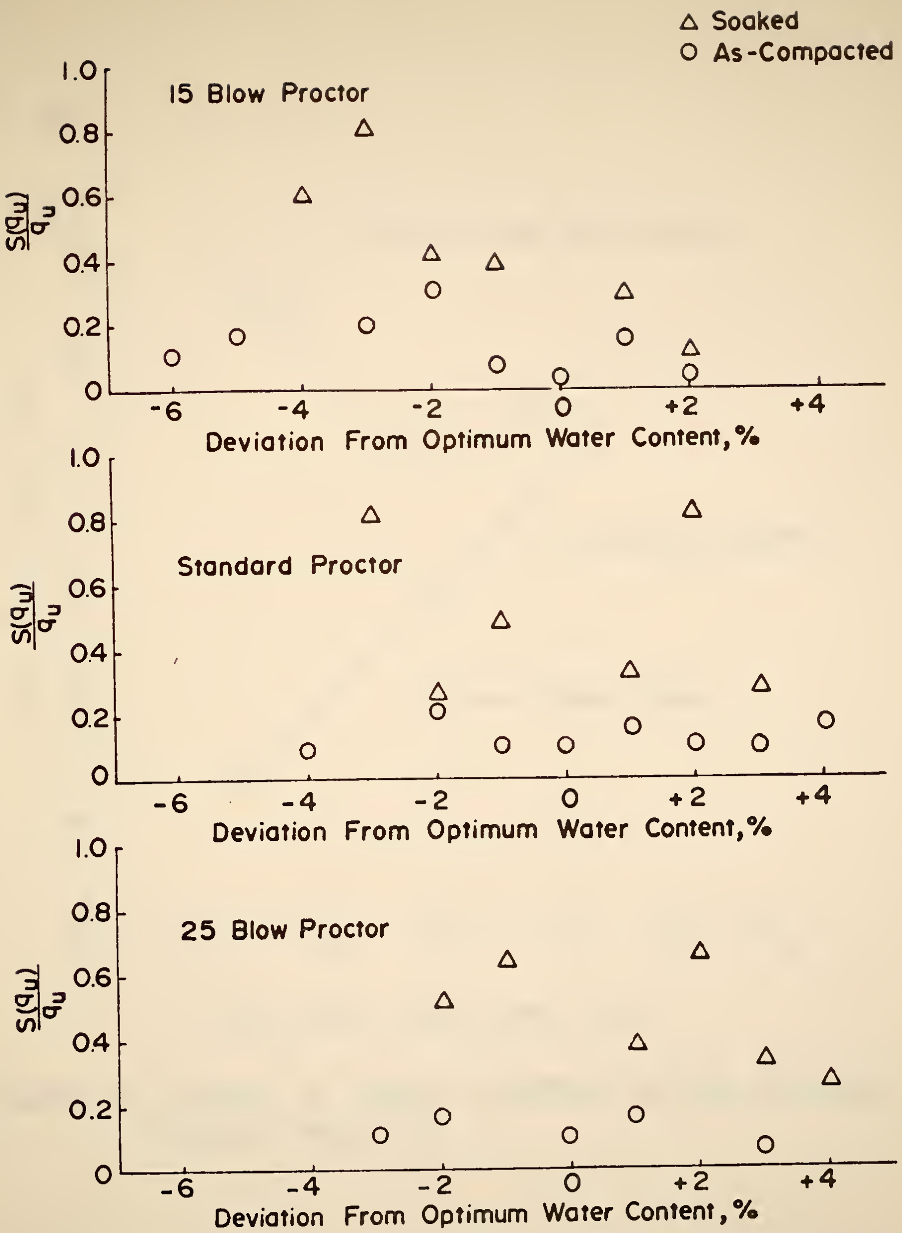

FIGURE 15 COMPARISON OF THE VARIATION OF SOAKED AND UNSOAKED STRENGTH.

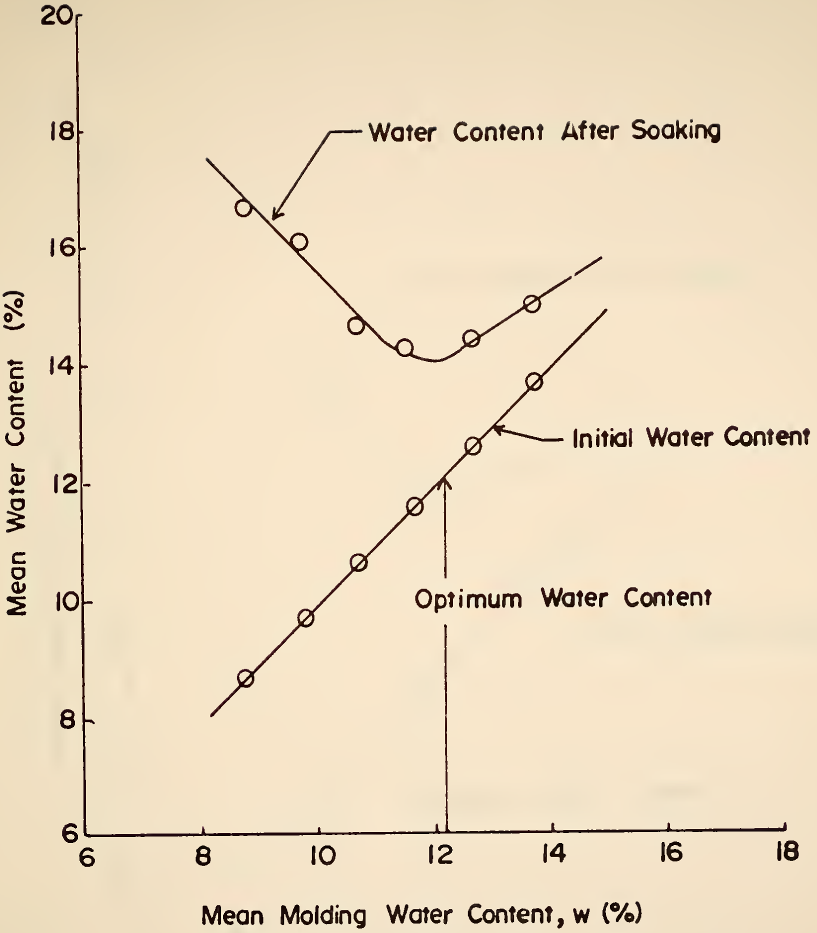

FIGURE 16 CHANGE IN WATER CONTENT AFTER SOAKING,
15 BLOW PROCTOR.

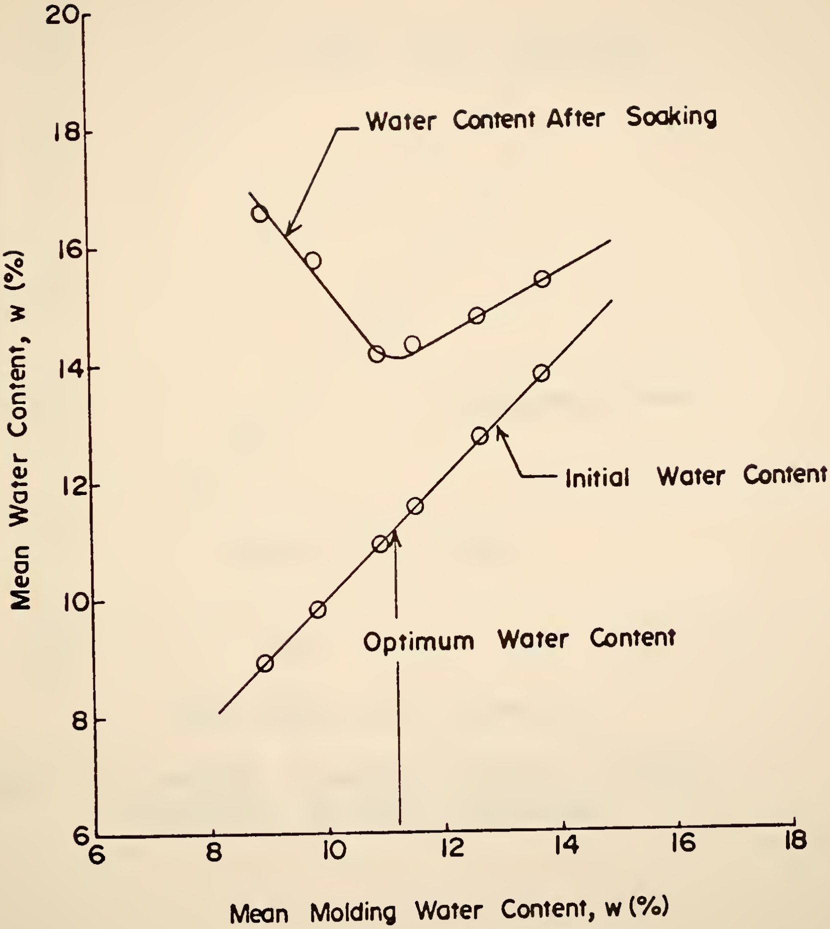

FIGURE 17 CHANGE IN WATER CONTENT AFTER SOAKING, STANDARD PROCTOR.

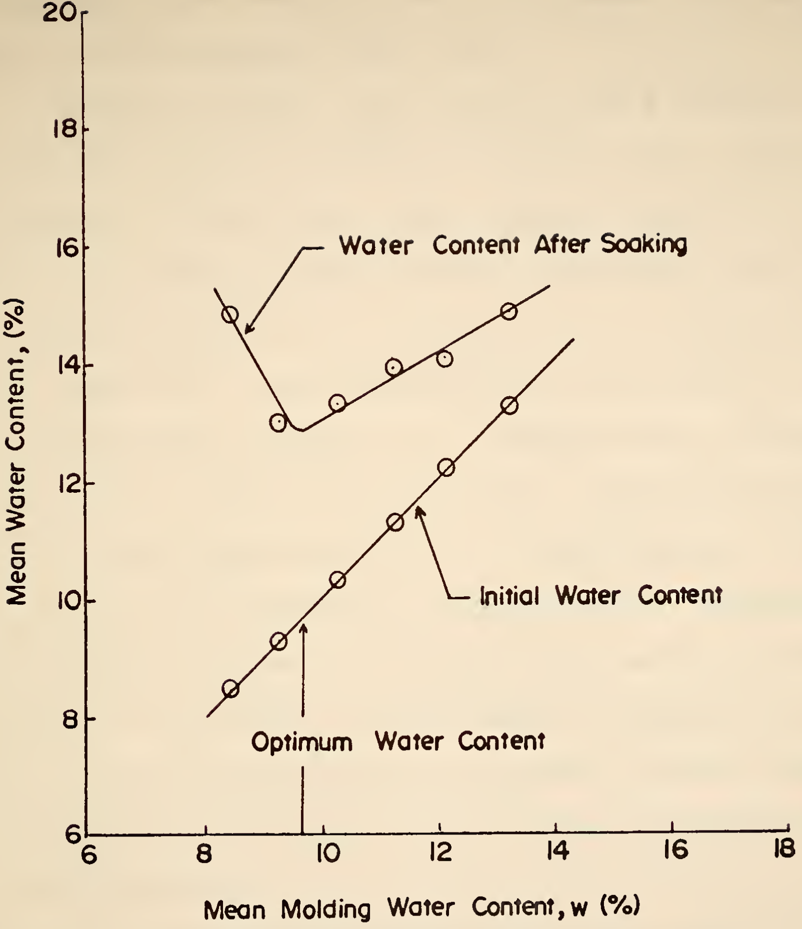

FIGURE 18 CHANGE IN WATER CONTENT AFTER SOAKING, 25 BLOW PROCTOR.

specimens compacted dry of optimum caused a larger strength loss than those compacted wet of optimum. This occurred for all three energy levels used.

The water content after soaking was a minimum for samples compacted at about the optimum water content for each respective energy level. For samples compacted wet of optimum, the change in water content upon soaking was less than samples compacted dry of optimum and was essentially constant. The reason for these observations is the type of structure developed during compaction. Compaction dry of optimum tends to produce a flocculated structure, random particle arrangement, while compaction wet of optimum produces a dispersed or more oriented structure (Lambe, 1958). Compaction dry of optimum also produces a greater water deficiency and a lower degree of saturation. Thus, samples compacted dry of optimum (flocculated structure) exhibited a greater water content change than samples compacted wet of optimum (dispersed structure).

Figure 19 shows data given by Wilson (1952) for a clayey sand. No change in water content occurred on the wet side of optimum yet a large change was experienced for the specimens compacted on the dry side. Seed et al. (1960) obtained data for the change in water content upon soaking for a sandy clay (CL). Their data is shown plotted in Figure 20. A large change in water content is noticed for specimens compacted dry of optimum and a much smaller change for

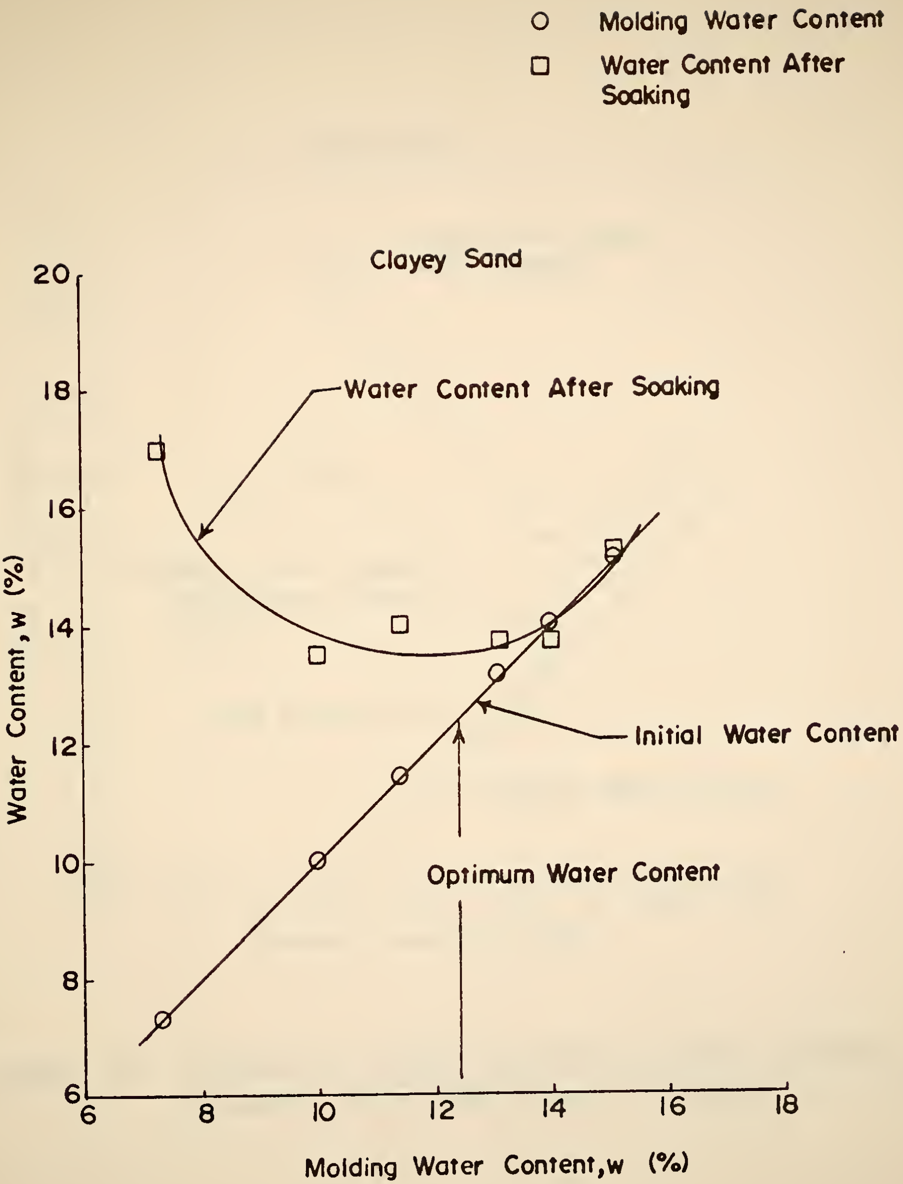

FIGURE 19 CHANGE IN WATER CONTENT AFTER SOAKING, HARVARD MINIATURE (WILSON, 1952).

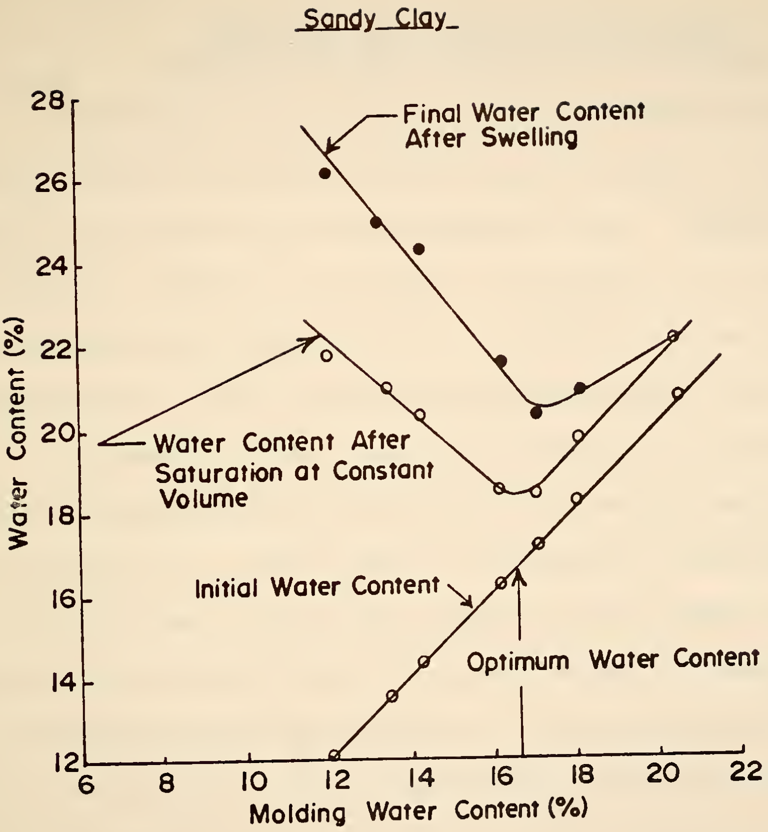

FIGURE 20 CHANGE IN WATER CONTENT AFTER SOAKING, HARVARD MINIATURE (Seed, et al. 1960).

ones compacted wet of optimum. The data obtained from this research is consistent with that obtained by Seed et al. (1960).

## Nomograms for Soaked Strength and Soaked Strength Variability Prediction

Nomography often times provides engineers with a simple and convenient means of presenting the results of empirical equations derived from experimental data. Through the use of nomograms, effects of changes in variables can be expressed graphically and readily seen. In addition, the solution of problems can often be delegated to those with little training.

Essigmann (1976) presented statistical relationships for the magnitude and variability of the as-compacted strengths for a silty clay in the form of a nomogram. His nomogram shows clearly the effects of dry density and the water content-dry density interaction on the magnitude of unconfined as-compacted strength. The variations in strength that are inherent in the compaction process are clearly shown by the magnitude of strength and the variation in dry density. The statistical results developed for the soaked strength magnitude and variability of soaked strength were also believed to be useful if provided in nomographic form. The nomograms developed for this research and by Essigmann (1976) provide the designer with a knowledge a priori of the influence of initial compaction conditions on the as-compacted and in-service strength properties of a silty clay.

Table 9 shows the statistical relationships used to develop and construct the soaked strength and variation in soaked strength nomograms. Three nomograms in all were constructed from the soaked strength results. Two nomograms were developed for the magnitude of soaked strength, one for specimens compacted dry of optimum and one for specimens compacted wet of optimum. The third nomogram prepared is a concurrency chart used to describe the variation in soaked strength.

The nomogram for the magnitude of soaked strength for specimens compacted dry of optimum is shown in two parts (Figures 21 and 22). This was necessary because of the complexity and the number of terms used to describe the dry side compacted soaked strength. To enter this nomogram (Part 1), one uses a dry density, water content, and energy ratio. From Part 1, one obtains the product of the squares of water content and energy and dry density and energy. These results are then entered in Part 2 (Figure 22) to predict the unconfined soaked strength that would result from the initial placement variables: dry density, water content, and energy. Since the relationship and hence the charts are somewhat complicated and involve several multiplications and additions, a key is provided in both Part 1 and 2.

The prediction of soaked strength for specimens compacted wet of optimum can be obtained using Figure 23. To predict the soaked strength, one simply enters Figure 23

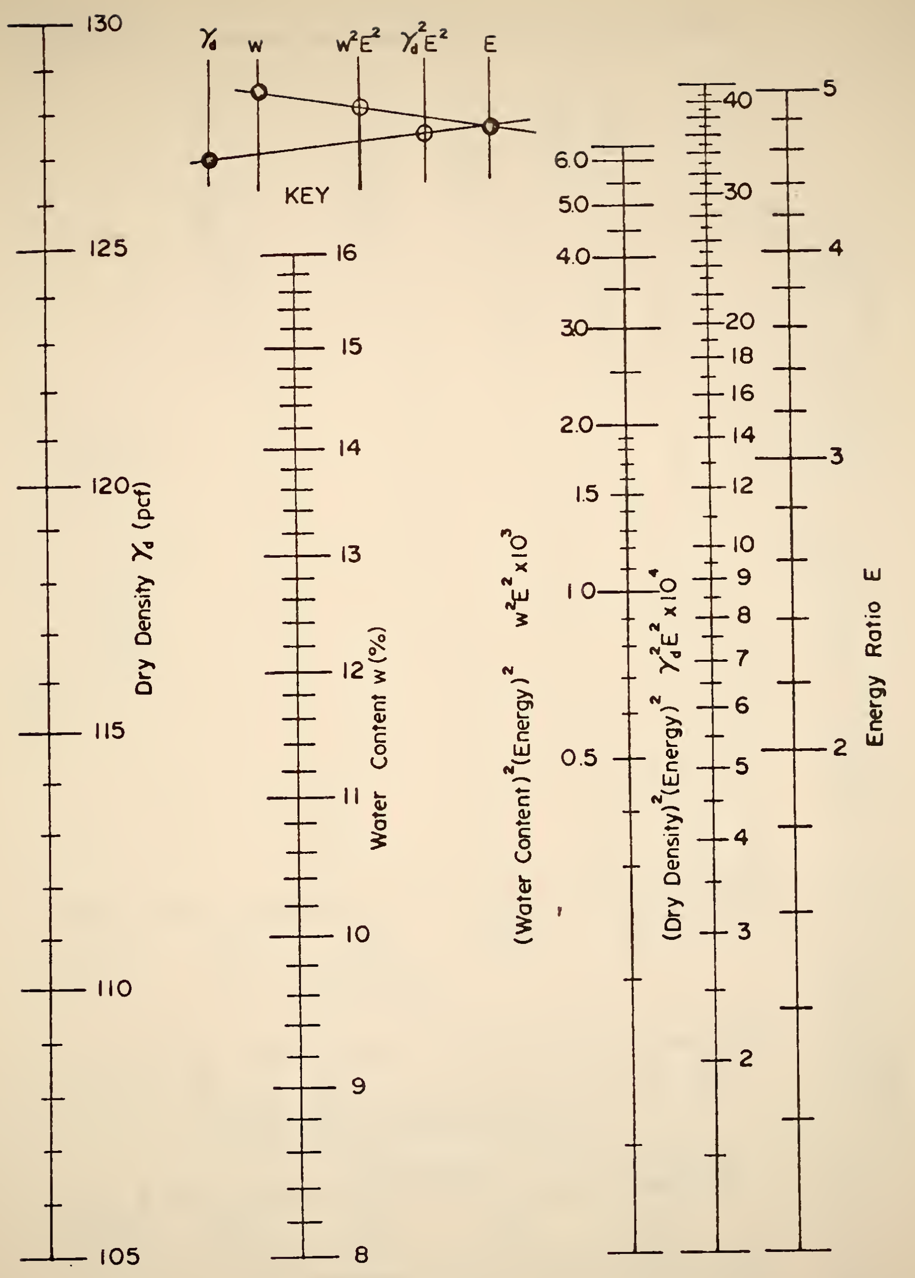

FIGURE 21 NOMOGRAM FOR SOAKED STRENGTH PREDICTION FOR MOLDING WATER CONTENTS DRY OF OPTIMUM, PART I.

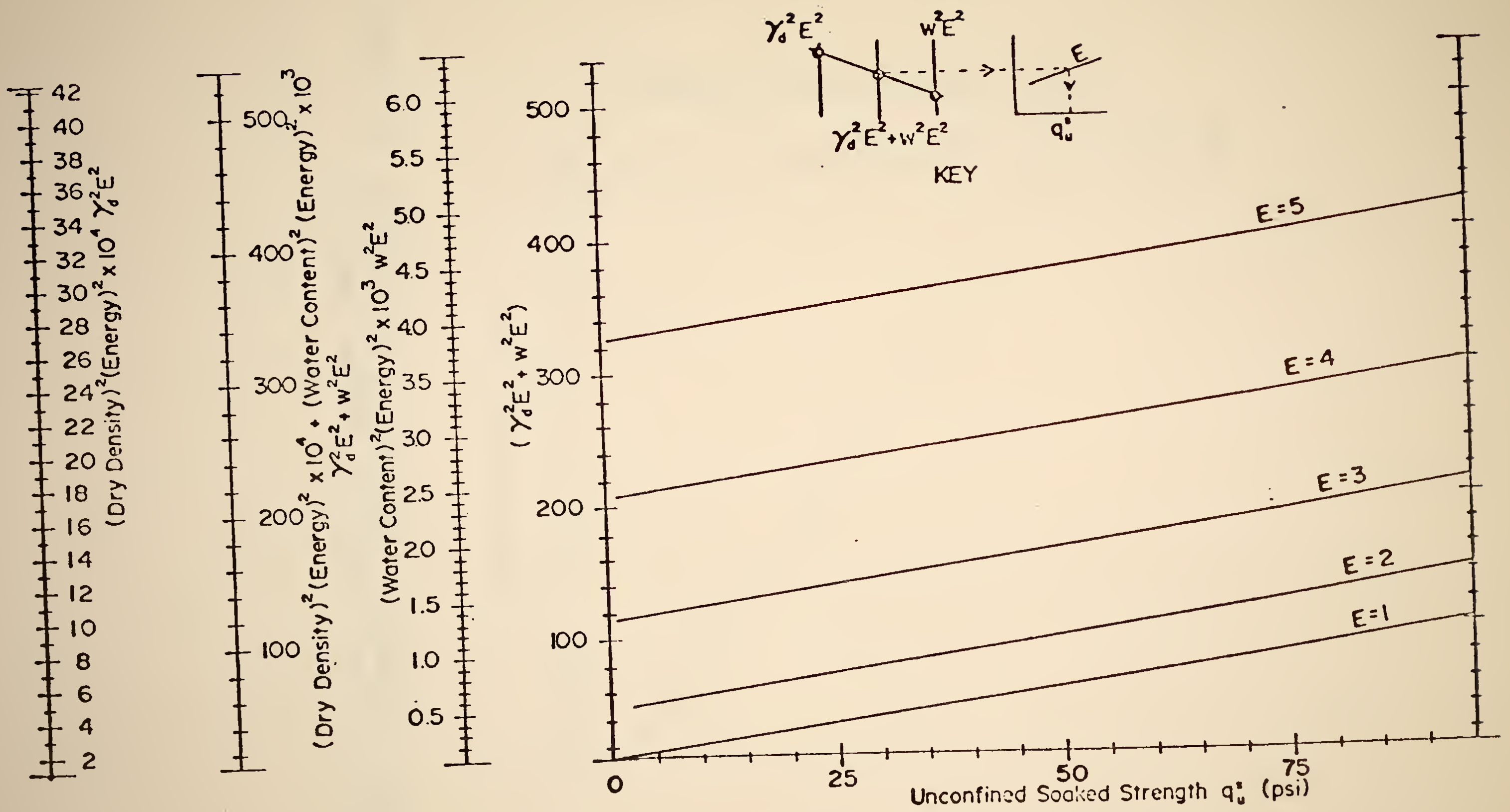

FIGURE 22 NOMOGRAM FOR SOAKED STRENGTH PREDICTION FOR MOLDING WATER CONTENTS DRY OF OPTIMUM, PART 2.

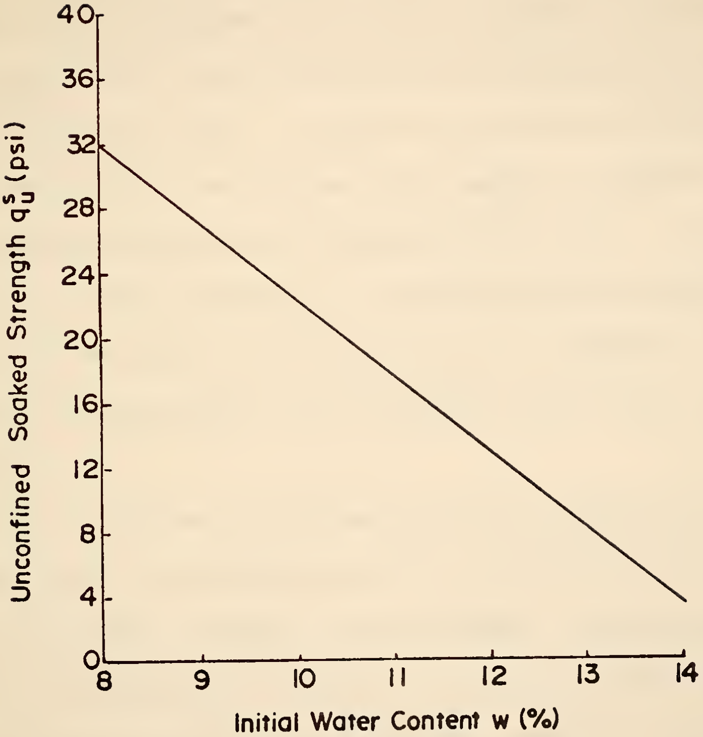

FIGURE 23 PREDICTION OF SOAKED STRENGTH FOR MOLDING WATER CONTENTS WET OF OPTIMUM.

with the molding water content and finds the resulting unconfined soaked strength. Together, Figures 21, 22, and 23 allow the accurate prediction of soaked strength for a range of molding water contents from 8% to 15%.

A concurrency chart shown in Figure 24 can be used to predict the variation in soaked strength. One merely enters this chart with a mean unconfined soaked strength and a molding water content. Figure 24 takes into account the interaction of water content and soaked strength. The variation one obtains is one standard deviation. It should be noted that the variation in soaked strength does not contain an energy variable, although energy is implicit in the soaked strength relationship for strengths dry of the optimum water content.

The nomograms developed from the results of this research can be used to establish initial placement variables for a desired soaked strength. For example, suppose one wanted to obtain a mean soaked strength, $\bar{q}_u^{\,s}$, of 10 psi compacted dry of optimum by the Standard Proctor method. Using Figure 22 (Part 2), the soaked strength and energy ratio of 10 psi and 1.67 respectively, locate the term $\gamma_d^{\,2}E^2 + w^2E^2 = 0.4$. Entering these values onto Figure 21 shows that the required mean soaked strength of 10 psi can be obtained at a water content-dry density combination of 11.7% - 117 pcf. Using Figure 24, the resulting variability one can expect is ± 4 psi. Other water content-dry density combinations can also

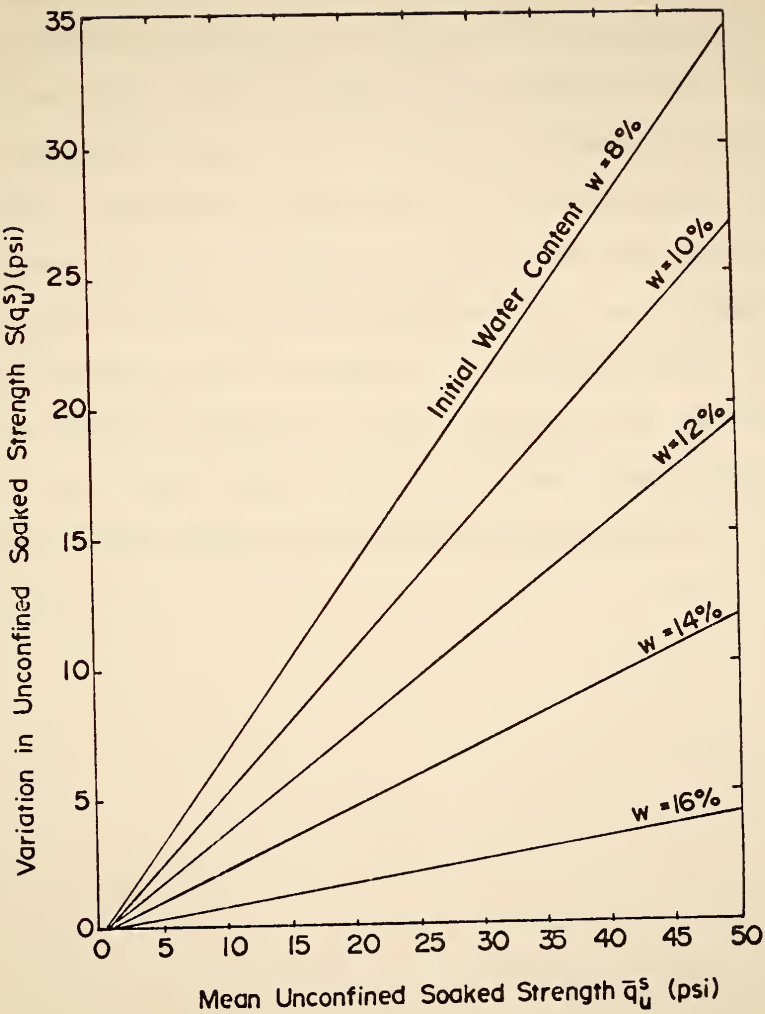

FIGURE 24 NOMOGRAM FOR SOAKED STRENGTH VARIABILITY PREDICTION.

be discovered to yield a soaked strength of 10 psi using the nomograms. If one desired the molding water content to be on the wet side of optimum, Figure 23 shows that for a desired soaked strength of 10 psi, the molding water content should be 12.7%. This results in a variation of ± 3 psi.

Nomograms similar to Figures 21 through 24 could be developed from actual field data. Controlled test pads using common pieces of compacting equipment and methods of construction can yield the necessary data to determine the field functional relationships. If this was done, the designer would then have a good handle on the in-service properties of the actual compacted mass. Compaction specifications could then be determined with sound and rational reasoning.

[illegible]

[illegible]

# CONCLUSIONS

As a result of this study which examined statistically the magnitude and variation of soaked strength for a silty clay compacted in the laboratory by the impact method, the following conclusions can be made:

1) For compaction dry of the optimum water content, the variables which control the unconfined soaked strength are the energy level, the interaction of dry density and energy, and the interaction of water content and energy.
2) For compaction wet of the optimum water content, the magnitude of the unconfined soaked strength is controlled solely by the molding water content.
3) The maximum soaked strength was obtained within a water content range of ± 1% of the optimum water content for the as-compacted state.
4) All energy levels show that the soaked strength decreases much more rapidly on the dry side of optimum than on the wet side.
5) The variation in soaked strength can be described by the magnitude of soaked strength and the interaction of water content and soaked strength for the entire range of water contents used in this investigation.

6) At a given water content interval, the variation of soaked strength relative to the mean soaked strength is larger than the variation of as-compacted strength relative to the mean as-compacted strength.

7) Under a low confining pressure, specimens compacted dry of optimum experience a larger change in water content upon soaking than those compacted wet of optimum. This resulted in the dry side specimens to experience a larger strength loss.

## RECOMMENDATIONS FOR FURTHER STUDIES

1. Further laboratory studies concerning soaked strength of compacted clays should be performed on a wide variety of clays.

2. The relative importance of field compaction variables should be examined in order to provide correlations between the laboratory and field soaked strengths.

3. Relationships, in terms of initial placement variables, for swelling pressures, prestress, and effective stress shearing parameters of compacted clays should be developed in the laboratory and the field. From these results, an attempt should be made to establish more rational compaction specifications.

4. Behavior studies should be studied for compacted clays subjected to repeated cycles of wetting and drying.

5. The improvement in the reliability of regression relationships using the Iterative Least Square Procedure when subpopulation variances are not constant should be investigated.

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# APPENDICES

## APPENDIX A:

## Table 10

## Experimental Data

Test Series: 15 Blow Proctor

| Dry Density (pcf) | Water Content (%) | Unconfined Soaked Compressive Strength (psi) |
|---|---|---|
| 110.4 | 8.5 | .5 |
| 110.0 | 8.7 | 1.0 |
| 113.8 | 9.0 | .3 |
| 111.6 | 9.4 | .8 |
| 114.2 | 9.4 | 1.5 |
| 114.7 | 9.7 | .9 |
| 113.0 | 9.9 | .5 |
| 114.6 | 9.9 | .3 |
| 120.6 | 9.9 | 3.0 |
| 118.1 | 10.0 | .9 |
| 119.7 | 10.3 | 2.5 |
| 122.2 | 10.3 | 4.0 |
| 120.8 | 10.8 | 2.6 |
| 121.9 | 10.8 | 4.6 |
| 122.0 | 11.1 | 6.8 |
| 124.6 | 11.2 | 7.1 |
| 122.5 | 11.3 | 5.0 |
| 122.4 | 11.5 | 12.3 |
| 123.0 | 11.5 | 8.5 |
| 122.4 | 11.6 | 8.9 |
| 122.9 | 11.6 | 12.8 |
| 121.0 | 12.1 | 4.5 |
| 121.7 | 12.1 | 14.0 |
| 122.2 | 12.5 | 8.0 |
| 123.1 | 12.5 | 5.5 |
| 124.0 | 12.6 | 5.1 |
| 119.5 | 12.7 | 4.2 |
| 123.5 | 12.7 | 9.7 |
| 125.7 | 12.7 | 8.0 |
| 124.8 | 12.8 | 6.7 |
| 120.2 | 13.4 | 4.5 |
| 119.3 | 13.8 | 4.0 |
| 123.6 | 13.8 | 5.6 |
| 120.6 | 13.9 | 4.7 |
| 121.3 | 13.9 | 4.7 |

Table 10. (Continued)

**Test Series:** Standard Proctor

| Dry Density (pcf) | Water Content (%) | Unconfined Soaked Compressive Strength (psi) |
|---|---|---|
| 114.9 | 8.8 | .5 |
| 116.5 | 8.8 | .7 |
| 115.4 | 8.9 | .6 |
| 117.0 | 8.9 | 1.3 |
| 118.6 | 8.9 | 1.7 |
| 118.7 | 8.9 | 3.8 |
| 119.0 | 9.1 | 1.3 |
| 120.4 | 9.6 | 1.9 |
| 121.5 | 9.8 | 1.4 |
| 123.9 | 9.8 | 1.9 |
| 117.9 | 9.9 | 2.5 |
| 121.3 | 9.9 | 2.8 |
| 123.5 | 10.6 | 12.4 |
| 124.1 | 10.6 | 11.0 |
| 123.0 | 10.7 | 5.7 |
| 122.5 | 10.9 | 15.5 |
| 123.3 | 10.9 | 4.3 |
| 121.6 | 11.0 | 2.4 |
| 122.3 | 11.0 | 9.5 |
| 123.0 | 11.1 | 8.7 |
| 124.4 | 11.1 | 7.7 |
| 123.2 | 11.3 | 8.0 |
| 122.0 | 11.5 | 15.0 |
| 122.0 | 11.5 | 19.0 |
| 121.3 | 11.6 | 16.2 |
| 120.0 | 12.3 | 12.3 |
| 120.9 | 12.3 | 12.2 |
| 117.5 | 12.8 | 8.2 |
| 119.7 | 12.8 | 6.9 |
| 121.2 | 13.0 | 6.9 |
| 118.1 | 13.4 | 6.7 |
| 119.1 | 13.4 | 6.0 |
| 120.0 | 13.5 | 7.8 |
| 120.7 | 13.5 | 6.9 |
| 117.5 | 13.7 | 6.2 |
| 120.0 | 13.8 | 6.3 |
| 120.9 | 13.8 | 6.7 |
| 116.1 | 14.0 | 4.3 |
| 120.9 | 14.0 | 2.2 |
| 118.0 | 14.1 | 8.2 |
| 119.8 | 14.1 | 5.6 |

Table 10. (Continued)

**Test Series:** 25 Blow Proctor

| Dry Density (pct) | Water Content (%) | Unconfined Soaked Compressive Strength (psi) |
|---|---|---|
| 124.1 | 8.1 | 3.7 |
| 125.1 | 8.1 | 2.1 |
| 123.2 | 8.7 | 9.5 |
| 125.4 | 8.7 | 6.6 |
| 125.7 | 8.7 | 8.1 |
| 124.6 | 8.8 | 10.7 |
| 125.4 | 8.8 | 12.1 |
| 127.7 | 9.1 | 25.0 |
| 129.2 | 9.5 | 21.0 |
| 125.2 | 9.5 | 36.1 |
| 129.4 | 9.5 | 63.3 |
| 126.7 | 9.7 | 26.4 |
| 127.0 | 9.7 | 20.3 |
| 125.8 | 9.8 | 28.2 |
| 127.8 | 10.0 | 35.9 |
| 128.0 | 10.0 | 26.1 |
| 123.1 | 10.5 | 16.0 |
| 123.1 | 10.5 | 20.5 |
| 124.1 | 10.5 | 12.5 |
| 124.2 | 10.5 | 17.7 |
| 124.5 | 10.5 | 14.6 |
| 123.0 | 10.9 | 12.0 |
| 125.1 | 10.9 | 12.1 |
| 125.1 | 11.1 | 37.9 |
| 124.2 | 11.6 | 18.1 |
| 123.0 | 11.7 | 9.6 |
| 127.6 | 11.7 | 10.2 |
| 120.5 | 11.9 | 16.3 |
| 121.5 | 11.9 | 20.0 |
| 122.9 | 11.9 | 10.9 |
| 124.6 | 12.1 | 10.4 |
| 127.4 | 12.1 | 9.4 |
| 126.4 | 12.3 | 8.5 |
| 115.4 | 12.7 | 10.7 |
| 124.9 | 12.7 | 12.7 |
| 120.9 | 13.2 | 8.8 |
| 119.7 | 13.3 | 8.2 |
| 124.5 | 13.3 | 5.1 |
| 122.7 | 13.4 | 9.2 |
| 123.2 | 13.4 | 5.0 |
| 124.2 | 13.4 | 6.3 |

## APPENDIX B:

### Table 11

### U.S. Customary - SI(International System) Conversion Factors

| To convert | To | Multiply by |
|---|---|---|
| inches (in) | millimeters (mm) | 25.40 |
| inches (in) | centimeters (cm) | 2.540 |
| inches (in) | meters (m) | 0.0254 |
| square inches (sq in) | square centimeters ($cm^2$) | 6.45 |
| cubic feet (cu ft) | cubic meters ($m^3$) | 0.028 |
| pounds (lb) | kilograms (kg) | 0.453 |
| tons (ton) | kilograms (kg) | 907.2 |
| pounds per square inch (psi) | kilonewtons per square meter ($kN/m^2$) | 6.9 |
| gallons (gal) | cubic meters ($m^3$) | 0.0038 |

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